HOW PLACEBOS WORK · BURYING PLUTONIUM UNDER THE SEA · LEONARDO'S LEGACY

SCIENTIFIC AMERICAN

JANUARY 1998 $4.95 U.K. £3.00

FLYING OVER THE SOLAR SYSTEM

THE ULYSSES SPACECRAFT GOES WHERE NO PROBE HAS GONE BEFORE

Life's architecture: cells grow with "tensegrity"

VICTORIANS ENJOY EASY ACCESS TO GOVERNMENT SERVICES

Multimedia technology is introducing people living in Victoria, Australia, to a whole new way of accessing government services. NEC Australia in partnership with Aspect Computing has teamed up in a world first to deliver public services on-line.

With the push of a button, or a click on a mouse, Victorians can now pay their water and electricity bills, order birth certificates, conduct transactions such as motor vehicle registration and update government documents such as electoral rolls. They can even get their dog licenses on-line.

This is just the beginning of a strategy to establish Victoria as a global 'center for multimedia excellence'. While the network currently offers 26 services provided by State and local government and energy and water utilities, the Victorian Government plans to have all government services available on-line by 2001.

To maximize community access, the new Electronic Services Delivery (ESD) network is being delivered in three ways–via Internet PCs at home or work; touch phones connected to an Interactive Voice Response system; or touch-screen kiosk terminals at shopping malls and other convenient public places.

This same ESD network will also be available to business–offering electronic commerce solutions as a new way of delivering services and information to customers. It's a service that will work for both government and business in Victoria–24 hours a day, every day of the year.

For further information, please contact NEC Corporation. Fax: +81-3-3798-6333
Visit our web site: http://www.nec.co.jp/newscope/

TERRESTRIAL TV TURNS TO DIGITAL

Following the trend set by satellite television, terrestrial TV is now stepping into the age of digital transmission. For viewers, the move to digital technology means more programs to choose from or enhanced video quality. To help broadcasters make the transition, NEC offers a broad range of solid-state digital TV transmitters.

NEC provides high-performance transmitters for both UHF and VHF bands. Output power ranges from 250W to 5kW in UHF, and from 250W to 3kW in VHF. Our digital transmitters interface easily with ATSC (US)- or DVB (European)-standard equipment.

Reliability is crucial for digital broadcasts. NEC has supplied more than 4,300 analog solid-state transmitters. They have established a record of outstanding reliability in broadcast facilities worldwide. Inheriting this tradition of reliable design, our digital transmitters feature new transistor power amplifier units. They incorporate high-gain, high-efficiency MOS FET devices, developed by NEC specifically for linear amplifiers.

Our digital transmitters also feature space-saving design and easy installation. They fit comfortably into existing transmitter rooms to facilitate analog/digital simulcasts.

NEC AT TELECOM INTERACTIVE 97

NEC displayed a broad range of hot new Internet technologies and multimedia service products at TELECOM Interactive 97. Organized by ITU, it was the first global exhibition dedicated to Internet and multimedia applications.

Our Internet solutions included the SiteCruise Theater, a theater-style automatic web browsing system and Network Video Audio Tool, an Internet broadcasting system.

Demonstrations of NEC Global Network Class also attracted many visitors. The virtual classroom on the Internet currently connects 92 schools in 34 countries.

NEC also displayed equipment now being introduced by the world's first commercial service to offer video-on-demand. Our VOD display included broadband access systems, advanced digital set-top boxes, ATM switches and HYPERMS servers for multimedia-on-demand.

Other exhibits included mobile computing with PHS (personal handyphone system) data transmission, Plasma/LCD monitors and FISHCLUB, a virtual aquarium using High Definition TV.

SINGLE-CHIP RISC DELIVERS 52MIPS

Can you increase performance while reducing component count? This is the challenge facing designers of embedded systems such as printers, DVD players and digital cameras. NEC's new 32-bit RISC microcontroller offers a powerful single-chip solution.

The V850E/MS1 microcontroller can process large volumes of data while providing highly precise realtime control. It executes 52MIPS at 40MHz/3.3V and 5V operation. That's faster than any other single-chip RISC in the world.

Our new microcontroller incorporates a 4-ch DMA controller and interfaces for many types of memory. It connects directly with external memories such as EDO DRAM, Page ROM and SRAM.

The 32-bit RISC device uses middleware to process diverse multimedia data. The middleware library includes JPEG, JBIG and MH/MR/MMR.

just imagine
NEC MULTIMEDIA

NEC

SCIENTIFIC AMERICAN

January 1998 Volume 278 Number 1

Scientific American (ISSN 0036-8733), published monthly by Scientific American, Inc., 415 Madison Avenue, New York, N.Y. 10017-1111.

Periodicals postage paid at New York, N.Y., and at additional mailing offices. Canada Post International Publications Mail (Canadian Distribution) Sales Agreement No. 242764. Canadian BN No. 127387652RT; QST No. Q1015332537. Subscription rates: one year \$34.97 (outside U.S. \$47). Institutional price: one year \$39.95 (outside U.S. \$50.95). Postmaster: Send address changes to Scientific American, Box 3187, Harlan, Iowa 51537. Reprints available: write Reprint Department, Scientific American, Inc., 415 Madison Avenue, New York, N.Y. 10017-1111; fax: (212) 355-0408. **Subscription inquiries: U.S. and Canada (800) 333-1199; other (515) 247-7631; e-mail to info@sciam.com**

About the Cover

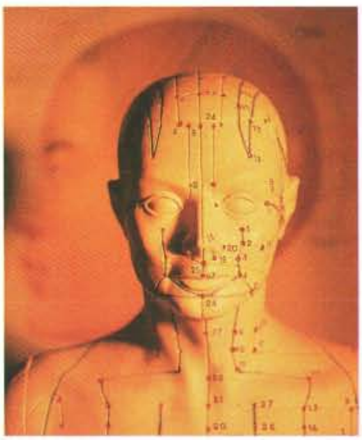
Geometric scaffolding inside cells seems to obey architectural principles identified by the engineer Buckminster Fuller, dynamically redistributing the structural stress. Painting by Slim Films.

Visit the Scientific American Web site (http://www.sciam.com) for more information on articles and other on-line features.

A Stab in the Dark

A recent stamp of acceptance given to acupuncture by the National Institutes of Health lends extra currency to this month's article "The Placebo Effect," by Walter A. Brown (page 68). A review panel organized by the NIH has endorsed the use of acupuncture as an alternative or complementary treatment for a miscellaneous host of ailments, including nausea from chemotherapy, lower back pain, dental pain, asthma, tennis elbow and carpal tunnel syndrome.

This development will not end the controversy over acupuncture's purported benefits, nor should it. Critics have argued that the review panel, while independent, lacked any voices sufficiently skeptical of the claims for acupuncture. And the panel itself recognized that better, more thorough trials are needed to test the technique's real therapeutic benefit. The best that can be said at present is that against some medical conditions, acupuncture seems to do no harm and may bring relief, although no one has more than a vague idea of how.



ACUPUNCTURE CHART shows targets for cryptic treatments.

IGNO CUYPERS World View/SPL/Photo Researchers, Inc.

The 2,500-year-old premise of acupuncture is that invisible *qi* energy flows through meridians in the body and that imbalances in this flow cause sickness. Acupuncture needles, positioned just so, restore the harmonious balance of *qi*. It is a lovely concept—and it is completely irreconcilable with empirical science. (Whether it corresponds metaphorically to some other physical or psychological dynamic affecting health is an argument for another time.) But if acupuncture does empirically demonstrate some benefit, if only as a palliative, then the mechanisms of its action will prove interesting to deduce. Some studies have shown that acupuncture raises the body's levels of natural painkillers like endorphins. That could explain the ultimate source of the relief, but it doesn't explain why needles in the skin should bring it or why some acupuncture points would be more appropriate than others.

One possibility is that acupuncture works through the placebo effect. The label "placebo" has often become a dismissive excuse not to think further about why many treatments bring relief as well as they do. Placebos may act psychologically, but it would still be undeniably interesting and valuable to know how a psychological phenomenon can mediate organic changes. Walter Brown argues that physicians should be open to employing placebos prudently when dealing with ailments that cannot be treated more directly, effectively or safely by traditional means. The medical sciences, after all, are still only part of the healing arts.

John Rennie

JOHN RENNIE, *Editor in Chief*
editors@sciam.com

LETTERS TO THE EDITORS

TOTAL RECALL

Thank you for publishing Elizabeth Loftus's article "Creating False Memories" [September 1997]. People need to be educated about the pain that can be caused by overzealous therapists. In June 1991 our then 30-year-old daughter began seeing a therapist for depression following her divorce. After seeing her for less than a month, this man analyzed her dreams and told her that the depression was from repressed memories of sexual abuse. Since then, she has broken all contact with us. Her siblings, however, do not believe the accusations. We have not only been falsely accused of a horrible crime, we have also lost a child.

HELEN DAVIS
Logansport, Ind.

Loftus's interesting article may leave readers with the impression that most allegations of abuse are inculcated by manipulative therapists. My daughter, who has Down syndrome, was molested for four years by her father, my ex-husband. Although I had begun to suspect him from her sexualized behavior and from the fact that there were no other opportunities in her protected life for sexual abuse to occur, it was impossible for me to believe that her father would do such a thing until I heard my daughter explicitly describing one of his acts and crying softly to herself that she loved him, that it couldn't be "that bad." We are all capable of embellishing the truth and, in some cases, inventing it under the power of repeated suggestion. But to make any generalizations about the incidence of child abuse based on a few spectacular cases of unscrupulous therapists is unfair to the many children who have been molested.

Name withheld by request

Loftus replies:

As Davis poignantly recounts, being falsely accused of sexual abuse and then losing a child are among the most painful experiences a parent can endure. The mother of the abused daughter also describes another agonizing life experience, that of slowly learning that her child was molested for years. Thousands of people, both parents and children, have needlessly suffered both abuse and false accusations of abuse. These letters remind us of two crucial endeavors: appreciating and curbing the madness of "memories" induced by suggestive therapy and devoting badly needed attention to the real horror of child abuse.

SINGING SANDS

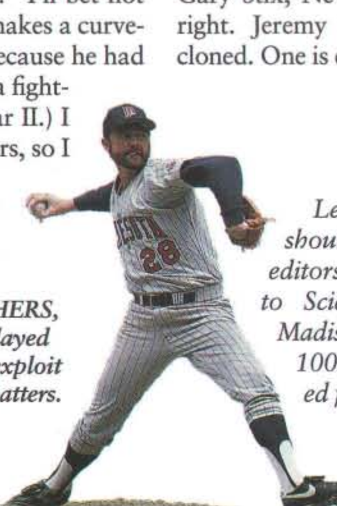
As a youngster, I remember hearing a popular song that I thought was called "The Singing Sands of Alamosa." For many years, I asked people if they recalled the song or knew that sands "sing," as described in "Booming Sand," by Franco Nori, Paul Sholtz and Michael Bretz [September 1997]. Even my wife began to look doubtfully at me, as she had never heard the song or the sands. A bit of library research revealed that the song was in the score of the 1942 movie *Always in My Heart,* with music by Bert Reisfeld and lyrics by Kim Gannon. It was recorded by Alvino Rey, a singer of the 1940s. I wonder if any of them ever heard the sands sing.

SIDNEY S. JACOBSON
Chester, N.J.

POLITICS OF BASEBALL

Alan M. Nathan's discussion of baseball pitches [Working Knowledge, September 1997] reminded me of an incident that occurred while I was pitching for the Washington Senators in 1969. It was the beginning of spring training, and Ted Williams was our new manager. Ted was fond of pointing out that pitchers were dumber than spaghetti. To prove it, he gathered all the pitchers together and challenged us: "I'll bet not one of you knows what makes a curveball curve." (Ted knew because he had learned about airflow as a fighter pilot during World War II.) I felt I had to defend pitchers, so I blurted out the explanation. This was followed by dead silence. Looking back on it, I suppose my surprising the new manager this way wasn't a career-enhancing move. Maybe I was dumber than spaghetti after all.

DAVID G. BALDWIN
San Diego, Calif.



***ACE CURVEBALL PITCHERS,** like Bert Blyleven, who played for the Minnesota Twins, exploit aerodynamics to surprise batters.*

MITCHELL B. REIBEL *Sports Photo Masters*

AIDS TREATMENT

I read with interest the article by Stephen J. O'Brien and Michael Dean, "In Search of AIDS-Resistance Genes" [September 1997]. It struck me that one therapeutic option seems to have been overlooked. Would it not be less fraught with complication to find a therapeutic agent that would irreversibly bind to the crucial CCR5 binding site on the HIV particle itself, thus preventing its binding to normal CCR5 receptor sites on the macrophages, which could then be left to perform their otherwise normal immune functions?

KOEN O. LOEVEN
Woodbury, Conn.

O'Brien and Dean reply:

The suggestion to target the CCR5 binding site of HIV with a blocking agent is a reasonable one, but it has some potential difficulties. The exact region of HIV that interacts with CCR5 is not known. Also, HIV unfortunately tends to evolve genetic resistance to immune factors such as antibodies and sensitized *T* lymphocytes and would likely do the same for synthetic blocking agents.

RIFKIN REDUX

As to the August 1997 profile of Jeremy "We Will Not be Cloned" Rifkin ["Dark Prophet of Biogenetics," by Gary Stix, News and Analysis]: he is right. Jeremy Rifkin should not be cloned. One is enough.

WILLIAM SHEELEY
Phoenix, Ariz.

Letters to the editors should be sent by e-mail to editors@sciam.com or by post to Scientific American, 415 Madison Ave., New York, NY 10017. Letters may be edited for length and clarity.

50, 100 AND 150 YEARS AGO

JANUARY 1948

THE NEW *SCIENTIFIC AMERICAN*—"Under new ownership and a new board of editors, the 103-year-old *Scientific American* is to become a magazine of all the sciences, covering the physical, biological and social sciences as well as their more significant applications in medicine and engineering."

AIRBORNE PROSPECTING—"Until recently geophysicists researching the earth's magnetic field sent out survey parties with a magnetometer. Frequently the party had to hack its way through the bush to collect data. It was slow, expensive work. Today geophysicists can use a dramatic refinement of this old method—the *airborne* magnetometer. Carried by an airplane traveling at 125 miles per hour at an altitude of up to 1,500 feet, the airborne magnetometer can deliver accurate data on new oil and mineral resources at a rate of up to 10,000 square miles per month."

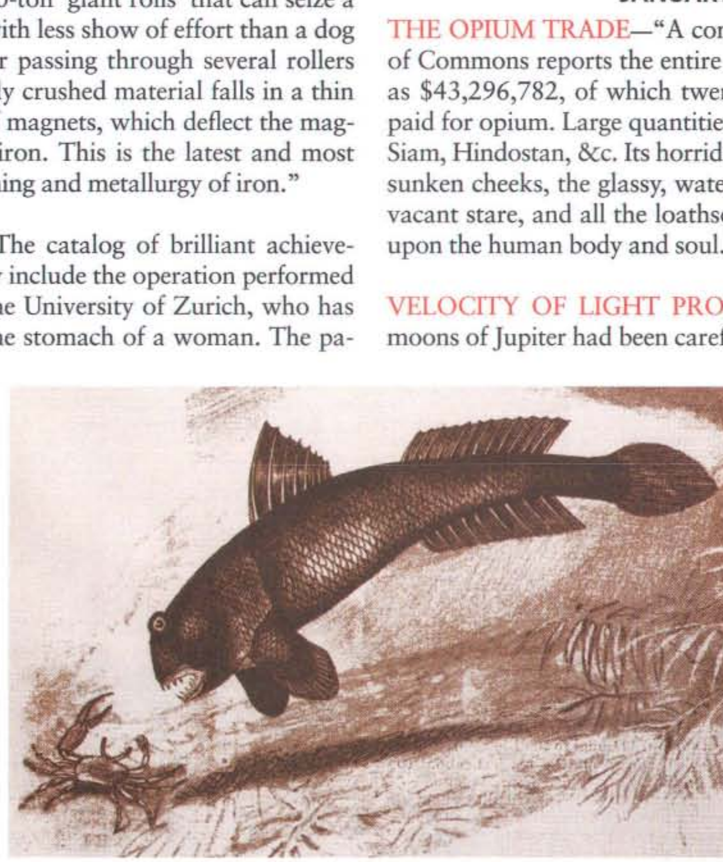
JANUARY 1898

EDISON'S OBSESSION—"The remarkable process of crushing and magnetic separation of iron ore at Mr. Thomas Edison's works in New Jersey shows a characteristic originality and freedom from the trammels of tradition. The rocks of iron ore are fed through 70-ton 'giant rolls' that can seize a 5-ton rock and crunch it with less show of effort than a dog in crunching a bone. After passing through several rollers and mesh screens, the finely crushed material falls in a thin sheet in front of a series of magnets, which deflect the magnetic particles containing iron. This is the latest and most radical development in mining and metallurgy of iron."

RADICAL SURGERY—"The catalog of brilliant achievements of surgery must now include the operation performed by Dr. Carl Schlatter, of the University of Zurich, who has succeeded in extirpating the stomach of a woman. The patient is in good physical condition, having survived the operation three months. Anna Landis was a Swiss silk weaver, fifty-six years of age. She had abdominal pains, and on examination it was found that she had a large tumor, the whole stomach being hopelessly diseased. Dr. Schlatter conceived the daring and brilliant idea of removing the stomach and uniting the intestine with the oesophagus, forming a direct channel from the throat down through the intestines. The abdominal wound has healed rapidly and the woman's appetite is now good, but she does not eat much at a time."

VERNE SURPASSED—"When Jules Verne wrote his fascinating book, 'Around the World in Eighty Days' [1873], he aimed to show the utmost that could be accomplished by the means of transportation of his day. A quarter of a century later we are near the day when the ordinary tourist can make the trip in less than half of eighty days. The Russian minister of communication has stated that when the great Trans-Siberian railroad is opened, early in the twentieth century, the tour of the world can be completed in thirty-three days."

JUMPING FISH—"The most interesting examples of amphibious fishes are found among the Gobies of the tropics. Our illustration is of a 'mudskipper' of the genus Periophthalmus. The head of this fish is large, the eyes conspicuous and protruding, the pectoral fins powerful, resembling legs more than fins and enabling it to jump along sands or muddy shores. When pursued they prepare to escape by taking to the land rather than to the water."



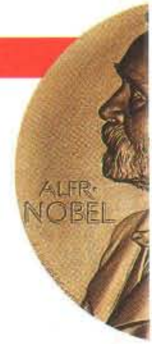
On land, a strange fish pounces on its prey

JANUARY 1848

THE OPIUM TRADE—"A committee in the British House of Commons reports the entire value of imports into China as $43,296,782, of which twenty-three million dollars are paid for opium. Large quantities are used in other countries, Siam, Hindostan, &c. Its horrid effects are seen in the sallow, sunken cheeks, the glassy, watery eyes, the idiotic look and vacant stare, and all the loathsome ruin that vice can bring upon the human body and soul."

VELOCITY OF LIGHT PROVED—"The eclipses of the moons of Jupiter had been carefully observed and a rule was obtained, which foretold the instants when the moons were to glide into the shadow of the planet and disappear, and then appear again. It was found that these appearances took place sixteen minutes and a half sooner when Jupiter was on the same side of the sun with the earth than when on the other side; that is, sooner by one diameter of the earth's orbit, proving that light takes eight minutes and a quarter to come to us from the sun."

The 1997 Nobel Prizes in Science



The achievements recognized by the Nobel Foundation in Stockholm span the range from controversial theory to well-grounded experiment

PHYSICS
LASER-COOLED ATOMS

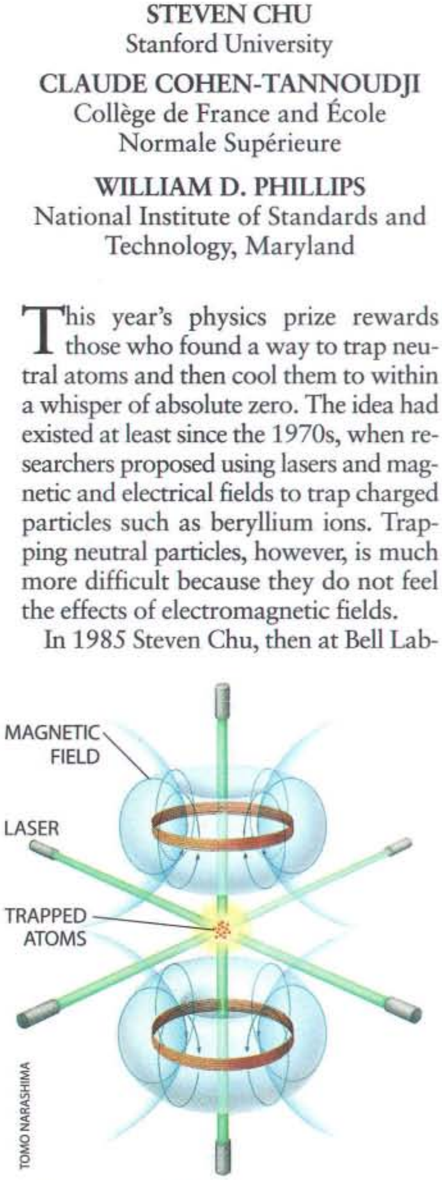
STEVEN CHU
Stanford University

CLAUDE COHEN-TANNOUDJI
Collège de France and École Normale Supérieure

WILLIAM D. PHILLIPS
National Institute of Standards and Technology, Maryland

This year's physics prize rewards those who found a way to trap neutral atoms and then cool them to within a whisper of absolute zero. The idea had existed at least since the 1970s, when researchers proposed using lasers and magnetic and electrical fields to trap charged particles such as beryllium ions. Trapping neutral particles, however, is much more difficult because they do not feel the effects of electromagnetic fields.

In 1985 Steven Chu, then at Bell Laboratories in Holmdel, N.J., and his colleagues placed sodium atoms in a vacuum chamber and surrounded them with six laser beams. The force exerted by the laser photons slowed the atoms. Chu found that the "optical molasses" chilled the atoms to 240 microkelvins (240 millionths of a Celsius degree above absolute zero), slowing them to about 30 centimeters per second (atoms in a room-temperature gas, in contrast, zip along at more than 100,000 centimeters—one kilometer—per second).



OPTICAL MOLASSES of six laser beams can slow atoms. Magnetic fields keep the atoms trapped and enable deeper cooling.

Unfortunately, gravity caused the slowed atoms to fall out of the optical molasses in about a second. William D. Phillips and others found that magnetic fields could affect the internal energy levels of atoms and hence exert a weak trapping force. In 1988 Phillips modified the optical molasses setup to include a slowly varying magnetic field above and below the point where the laser beams intersected. As a result, atoms were trapped for much longer.

Surprisingly, Phillips found that the magneto-optical trap could achieve a temperature of 40 microkelvins, much lower than the limit calculated by previous workers. Claude Cohen-Tannoudji and his colleagues explained how such deep cooling took place and showed that it could go even further: his team chilled helium atoms to 0.18 microkelvin. The cooling occurred because atoms can assume a "dark state," that is, a state in which they do not react to light. In that condition, a cooled atom is more likely to remain still.

Researchers have refined these cooling techniques over the years. For instance, the method called evaporative cooling ejects the hotter, more energetic atoms out of the trap. The technique led in mid-1995 to the creation of the Bose-Einstein condensate: atoms so cold that they act in unusual, collective ways.

The ability to control matter with light may lead to several applications. One is making more accurate clocks. Roughly speaking, slow-moving atoms could be excited so as to emit photons with frequencies so well defined that they could serve as a time standard. In principle, such timepieces would be 100 to 1,000 times more precise than existing atomic clocks, which lose no more than one second every million years. Trapping with lasers has also led to devices such as "optical tweezers," which can manipulate material as small as DNA strands, and to ultraprecise atom interferometers, which give atoms two paths to reach the same point and are often used to explore fundamental physics.

From *Scientific American*
COOLING AND TRAPPING ATOMS. W. D. Phillips and H. J. Metcalf, March 1987.
LASER TRAPPING OF NEUTRAL PARTICLES. Steven Chu, February 1992.
ACCURATE MEASUREMENT OF TIME. W. M. Itano and N. F. Ramsey, July 1993.

CHEMISTRY
THE MECHANISM OF LIFE

PAUL D. BOYER
University of California at Los Angeles

JOHN E. WALKER
Medical Research Council Laboratory of Molecular Biology, Cambridge, England

JENS C. SKOU
Aarhus University, Denmark

Living cells need the energy in the compound adenosine triphosphate (ATP) to power their essential functions. And they need a lot of it: every

AP/WIDE WORLD PHOTOS

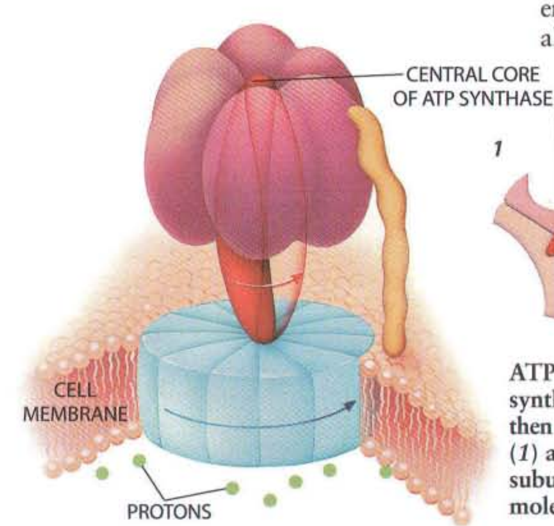
day a resting adult consumes roughly half of his or her body weight—about 40 kilograms—in ATP. Body weight does not fluctuate wildly, though, because cells can regenerate their stores of ATP from its breakdown products. The recipients of this year's chemistry Nobel have uncovered critical details about an important way in which ATP is used and how the recycling process works.

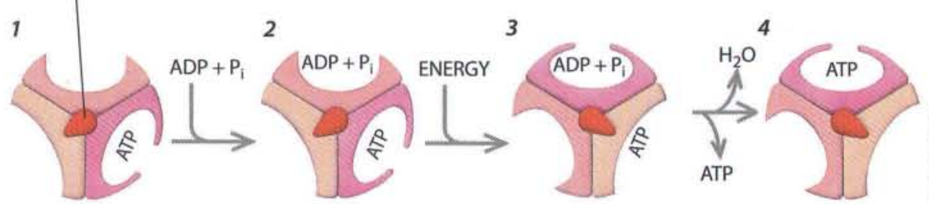
For the latter accomplishment, one half of the prize was split between Paul D. Boyer and John E. Walker. Boyer and Walker have studied how the enzyme known as ATP synthase catalyzes the formation of ATP from adenosine diphosphate, or ADP.

The interchange between ATP and ADP is crucial for providing a continual input of energy to the cell. When one of the high-energy phosphate bonds in ATP breaks, energy is released and diverted to tasks such as muscle contraction, the transport of ions across cell membranes or the synthesis of new compounds. Cells convert ADP back to ATP by re-forming the phosphate bond with the help of ATP synthase.

Boyer's research work, which began in the 1950s, focused on the mechanism by which ATP synthase assists in the formation of ATP. The enzyme consists of several subunits, which Boyer determined work together like gears, first attaching to ADP and a phosphate group and then churning out ATP. Walker's efforts to clarify the three-dimensional structure of ATP synthase verified this mechanism conclusively in 1994.

The second half of the prize was awarded to Jens C. Skou for his discovery in 1957 of the enzyme sodium, potassium-stimulated adenosine triphosphatase (Na^+, K^+-ATPase). This protein breaks down ATP and uses the liberated energy to transport sodium and potassium ions across cellular membranes, maintaining the proper balance inside the cell. With this finding, Skou became the first to identify an enzyme that controls the movement of ions across the cellular membrane. Later, other so-called ion pumps were identified. Because they typically regulate vital processes, they have become targets for many medications. For instance, drugs to treat stomach ulcers work by interfering with the ion pump that controls the release of hydrochloric acid in the stomach.





TOMO NARASHIMA

ATP CATALYSIS begins when protons pass through the part of the enzyme ATP synthase that lies in the cell membrane, causing it to turn (*left*). The central core (*red*) then rotates inside the top half of the enzyme (*purple*). This region holds an ATP molecule (*1*) and pulls in ADP and an inorganic phosphate group, P_i (*2*). As the core rotates, the subunit with ATP loosens, and the section holding ADP closes (*3*). The original ATP molecule is released, and a new one is formed from ADP (*4*). The cycle repeats.

PHYSIOLOGY OR MEDICINE
THE PRION PROPONENT

STANLEY B. PRUSINER
University of California
at San Francisco

The 1997 Nobel Prize in Physiology or Medicine goes to Stanley B. Prusiner, for his controversial "pioneering discovery" that a new type of infectious agent called a prion can cause an important group of fatal diseases. In these maladies, called transmissible spongiform encephalopathies (TSEs), the brain develops a spongy appearance. They include "mad cow" disease, scrapie in sheep, and Creutzfeldt-Jakob disease and kuru in humans. The diseases can be transmitted between species by injecting infected brain tissue into a recipient animal's brain. TSEs can also spread via tissue transplants and, apparently, food. Kuru was common in the Fore people of Papua New Guinea when they practiced ritual cannibalism, and mad cow disease is believed to have spread in the U.K. because cattle were fed unsterilized bonemeal from cattle carcasses.

Moved by the death of a patient to study Creutzfeldt-Jakob disease, Prusiner became interested in the early 1970s in the then heretical notion that the TSE agent lacks both DNA and RNA, the nucleic acids that constitute the genes of all other pathogens. One clue was that although nucleic acids are usually sensitive to radiation, infectious TSE preparations were highly resistant.

In 1982, after failing to detect genes that might point to a virus in infectious extracts, Prusiner named the enigmatic TSE agent a prion, for "proteinaceous infectious particle." He isolated a distinctive prion protein and proposed that TSEs can be triggered by it alone.

In the 15 years since, he and others have established the essential role of prion protein in TSEs. The Nobel Assembly at the Karolinska Institute in Stockholm has recognized the "unwavering" Prusiner for finding "a new biological principle of infection." The insight might allow the development of treatments.

Yet the idea that prion protein alone prompts TSEs still lacks unambiguous proof [*see box on next page*]. Only further experiments will reveal whether the Nobel Assembly was hasty.

From *Scientific American*

THE PRION DISEASES. Stanley B. Prusiner, January 1995.

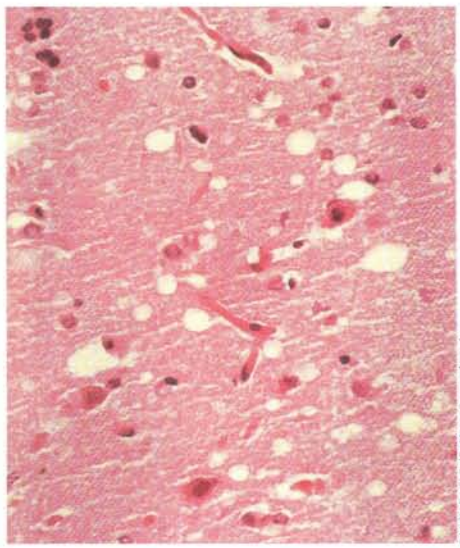
DEADLY ENIGMA. Tim Beardsley in News and Analysis, December 1996.

Can a Maverick Protein Really Cause Brain Disease?

Nobel prizes are usually awarded for achievements that have won universal acceptance. This time the Nobel Assembly in Stockholm broke with that tradition. In awarding the 1997 prize in physiology or medicine to Stanley B. Prusiner, the assembly honored the chief architect of a startling biological theory that is still not accepted by some experts.

In the 1970s Prusiner adopted an earlier speculation that TSEs could be caused by a protein acting alone. In the mid-1980s the theory edged into the mainstream when he and other researchers established that all mammals, so far as anyone knows, have naturally in their cells a gene encoding the prion protein. Normally, the gene gives rise to a harmless form of the protein. But this form apparently sometimes flips into a variant shape, which is insoluble and is often found in the brains of TSE victims.

Prusiner's theory holds that if some of the insoluble form finds its way into a mammal's brain, it can encourage the normal form to change into the supposedly pathological insoluble variant. One notable experiment, performed by Charles Weissmann of the University of Zurich, showed that genetically engineered mice lacking the prion protein gene are immune to infection with TSEs. Later he demonstrated that if brain tissue with the prion protein gene is grafted into such mice, the grafted tissue—but not the rest of the brain—becomes susceptible to TSE infection.



HOLES IN BRAIN TISSUE are left by Creutzfeldt-Jakob disease, a TSE.

Yet perplexities remain. Nobody knows, for example, why 100,000 insoluble prion protein molecules are needed to form an infectious dose. Furthermore, although the insoluble form can be made soluble and then regenerated, this reconstituted insoluble material is no longer harmful. Nor is it clear why, according to Laura Manuelidis of Yale University, the infectious component in a brain extract seems to consist of particles that contain only a small fraction of the allegedly pathological prion protein.

Manuelidis believes TSEs are actually transmitted by viruses. She points out that infectious TSE preparations do contain RNA sequences. But because nobody has been able to implicate the RNA in infectivity, most researchers dismiss it.

Prusiner and his associates point to experiments that suggest that if there is any essential DNA or RNA in a prion, the amount must be less than 100 bases—too few for a normal gene and therefore evidence of a new type of infection. Critics note, however, that such estimates rely on a highly inaccurate assay for infectivity—waiting to see whether injected mice get sick. So, they argue, a small undetected gene could in fact be hiding inside a prion.

A small gene within the prion might help explain the abiding mystery of strains. Many TSEs exist in distinguishable variants, even in animals that have identical innate prion protein genes. Prusiner's theory supposes that insoluble prion protein can assume a variety of different shapes, each able to replicate itself. Skeptics find that hard to believe.

According to Prusiner, experiments performed in his laboratory with transgenic animals clinch his theory. People with some specific mutations in their prion protein gene have an increased chance of developing a TSE, perhaps because their particular version of the healthy prion protein flips by itself into the bad form. Prusiner has made mice that produce large amounts of a mutant prion protein found in inherited cases of a human TSE. These engineered mice develop a TSE-like disease spontaneously. What is more, their brain tissue can transmit brain disease to other mice that have been genetically engineered to be especially receptive.

Yet Byron W. Caughey of Rocky Mountain Laboratories observes that the amount of infectivity in the brains of the spontaneously sick mice is "many orders of magnitude lower" than that found in brains clearly infected with a diagnosed TSE. And Caughey's colleague Bruce Chesebro, who disputes the prion theory, notes that the brains of the spontaneously ill mice in Prusiner's experiments contain undetectable amounts of the supposedly crucial insoluble prion protein.

Even more troubling, the spontaneously sick mice failed to transmit disease convincingly to normal, unengineered mice. Chesebro believes the spontaneously ill mice in Prusiner's tests did not have a genuine TSE.

Mystery also surrounds how the healthy form of prion protein converts into the insoluble form. Caughey and others have converted small amounts in a cell-free experiment. But some extract from an infected brain always has to be present, and there is no proof that the newly created protein can itself bring about disease. Caughey acknowledges that the added extracts might contain some vital unknown ingredient. The final proof of the prion theory, researchers agree, will come only when someone can make certifiably pure insoluble prion protein in a nonbiological system and show that it induces a TSE.

Some scientists in the antiprion camp worry that Prusiner's recognition will make it harder to fund experiments on alternative theories of TSEs. "Nobody wants to listen to anything except prions," Manuelidis complains. Prusiner has said his scientific opponents are "throwing up roadblocks."

But David Baltimore, president of the California Institute of Technology, says determined investigators can usually find some funding. And he believes researchers will feel that "as the target gets bigger, nothing would be better than to knock it off its pedestal." Baltimore, who shared a Nobel Prize in 1975 for groundbreaking studies of retroviruses, believes Prusiner's work could lead to broadly important insights into proteins. By honoring Prusiner, Baltimore adds, "we honor the sort of renegade who is good for science."

—Tim Beardsley in Washington, D.C.

ECONOMICS

WALL STREET ROCKET SCIENCE IN A POCKET CALCULATOR

ROBERT C. MERTON
Harvard University

MYRON S. SCHOLES
Stanford University

The abstruse mathematical reasoning behind the theory that wins the economics Nobel is often far beyond the grasp of all but a select few sophisticates. Yet the work of the 1997 prizewinners shared no such fate. In the early 1970s Myron S. Scholes and his now deceased collaborator, Fischer Black, had difficulty finding a journal that would accept a paper describing a differential equation for pricing the value of stock options and other securities that later came to be called derivatives. Once published, however, the formula—which Robert C. Merton helped to refine—gained immediate acceptance. Within months, traders began to use the Black-Scholes equation, punching the required variables into calculators to better analyze their buy-and-sell orders.

Options and other derivatives are contracts whose value is tied to an underlying asset, such as a stock, bond or currency. An option gives the buyer the right—but not the obligation—to buy or sell a security at a given price during a predetermined period. A put option, which gives the right to sell a holding at a certain price, functions as a kind of insurance policy against a decline in the market value of an investor's assets.

Using options to hedge against fluctuations in the value of the yen would allow a U.S. semiconductor manufacturer to concentrate on designing new chips without having to worry about how the vagaries of currency exchange rates will affect its bottom line for sales of new microprocessors in Japan. The price of the option, called the premium, is the cost the company pays to transfer to another party the risk of a precipitous fall in the value of the yen. Interest in valuing options dates back at least to 1900, but no one had good methods for determining what an option should be worth, so it was difficult to understand the risks that were involved in a transaction.

Black and Scholes's differential equation (related to a physics heat-transfer equation) requires a set of variables, such as current interest rates and the price of the underlying stock, most of which are available on the traders' screens or even from the pages of the *Wall Street Journal*. This pragmatic but quantitative approach to the valuation of a security helped to usher in the era of the "rocket scientist" as financial analyst—introducing the numerical skills of physicists and mathematicians to Wall Street.

The Nobel Prize section was reported by Tim Beardsley, Sasha Nemecek, Gary Stix and Philip Yam.

Risky Business

Derivatives may have won a Nobel, but are they really a good idea? Companies have suffered huge losses trading in the type of derivative financial products whose invention was facilitated by the work of Fischer Black and the Nobelists.

Options and other derivatives—including futures, forwards and swaps—are instruments for speculation as well as hedges against a drop in an asset's value. They can be used to bet that the price of an asset will go up or down. Derivatives also can have more of an effect on a portfolio than simply buying or selling a stock or bond because of the leverage involved. Last November, for instance, an investor could buy nearly $1 million in futures contracts on the Standard & Poor's 500 Index for about $40,000 down, less than 5 percent of the cost of buying the stocks themselves. (A futures contract is an obligation to buy a security on a certain date at a given price.) Such leveraging can turn a relatively small amount of cash into big gains or losses. If the market drops by 20 percent, the holder of the contracts would have to come up with almost $200,000 to match the decline in value of the underlying stocks.

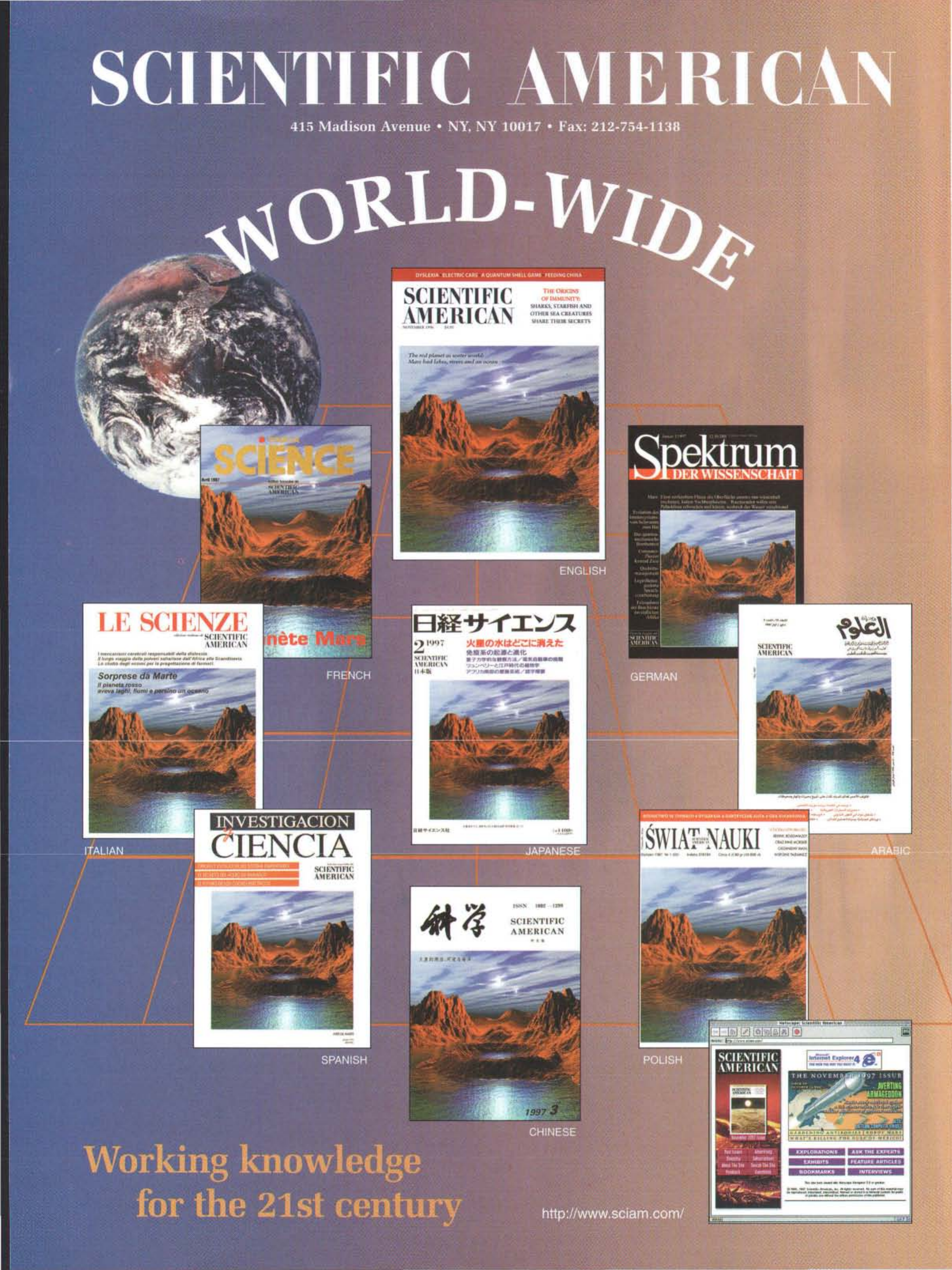
Derivatives can be highly complex financial instruments. A security, for example, may pay more interest as rates drop. These offspring of the era of Wall Street "rocket science" may befuddle corporate treasurers and board members, leaving them uncertain whether they have bought insurance or a lottery ticket. The big financial-center banks that sell derivatives, moreover, may have an incentive to push a product without clearly explaining the risks to a customer. "You see a gap between the sophistication of Wall Street firms and the client firms," notes Suresh M. Sundaresan of the Columbia University Graduate School of Business. "Because bonuses on Wall Street are tied to transaction volume, this creates an obvious problem."

One fear is that losses in the trading department of a large bank, say, could cause a meltdown of the financial system, a scenario that has sometimes prompted calls for stricter regulation. Critics of government meddling note that these dire warnings have never materialized. "The banks of the world have lost an order of magnitude more money on real estate than they'll ever lose on derivatives," says Merton H. Miller, a Nobelist in economics from the University of Chicago, who helped Scholes and Black get their original paper published.

BRAD LA PAYNE *Liaison International*

CHICAGO BOARD OPTIONS EXCHANGE is the world's largest options market.

Even if derivatives do pose hazards, they create opportunities for managing risks, even for the average consumer. Banks let a homeowner refinance a mortgage at a lower rate when interest rates fall because they can hedge their risk by trading derivatives backed by mortgages or government bonds. The message behind this frenzy of activity, Miller says, is simple: "Derivatives are here to stay, guys. Get used to them." —*Gary Stix*


SCIENTIFIC AMERICAN
415 Madison Avenue • NY, NY 10017 • Fax: 212-754-1138
WORLD-WIDE
DYSLEXIA · ELECTRIC CARS · A QUANTUM SHELL GAME · FEEDING CHINA
SCIENTIFIC AMERICAN
THE ORIGINS OF IMMUNITY: SHARKS, STARFISH AND OTHER SEA CREATURES SHARE THEIR SECRETS
The red planet as water world: Mars had lakes, rivers and an ocean
ENGLISH
SCIENCE
FRENCH
Spektrum DER WISSENSCHAFT
GERMAN
LE SCIENZE
SCIENTIFIC AMERICAN
Sorprese da Marte
Il pianeta rosso aveva laghi, fiumi e persino un oceano
ITALIAN
日経サイエンス
2 1997
SCIENTIFIC AMERICAN
火星の水はどこに消えた
JAPANESE
SCIENTIFIC AMERICAN
ARABIC
INVESTIGACION Y CIENCIA
SCIENTIFIC AMERICAN
SPANISH
科学
SCIENTIFIC AMERICAN
1997 3
CHINESE
ŚWIAT NAUKI
POLISH
SCIENTIFIC AMERICAN
EXPLORATIONS
ASK THE EXPERTS
EXHIBITS
FEATURE ARTICLES
BOOKMARKS
INTERVIEWS
Working knowledge for the 21st century
http://www.sciam.com/

NEWS AND ANALYSIS

IN FOCUS

BURYING THE PROBLEM

Could pumping carbon dioxide into the ground forestall global warming?

ANDREW HOLBROOKE *Liaison International*

***INDUSTRIAL EMISSIONS** of carbon dioxide need not always waft upward.*

In December world leaders gathered in Kyoto, Japan, to grapple with the growing threat of global warming caused by the burning of fossil fuels. To combat the surge in greenhouse gases—chiefly carbon dioxide—researchers and policymakers have called for energy conservation, taxes on carbon emissions and the swift development of renewable energy sources, such as wind and solar power. Still, with nuclear energy out of favor and no easy replacement for fossil fuels on the horizon, the rise in atmospheric carbon dioxide might appear unstoppable. But a growing number of scientists are pointing out that another means of combating greenhouse warming may be at hand, one that deals with the problem rather directly: put the carbon back where it came from, into the earth.

The idea of somehow "sequestering" carbon is not new. One method is simply to grow more trees, which take carbon from the atmosphere and convert it to woody matter. Although the extent of plantings would have to be enormous, William R. Moomaw, a physical chemist at Tufts University, estimates that 10 to 15 percent of the carbon dioxide problem could be solved in this way.

Other scientists, engineers and energy planners advocate placing the carbon where it does not contact the atmosphere at all. Howard J. Herzog of the Massachusetts Institute of Technology, for instance, proposes pumping carbon dioxide into the deep ocean. Although that tactic might be viewed as exchanging one form of pollution for another, there are good reasons to consider making the trade. The ocean contains at least 50 times more carbon than the atmosphere does, so adding the carbon dioxide from the burning of fossil fuels to the sea would have a proportionally smaller effect.

Advocates of this fix also point out that much of the carbon dioxide now released finds its way into the ocean anyway, disturbing the chemistry of the surface waters. Purposefully placing it at greater depth should do less harm, because hundreds of years would elapse before the dissolved carbon dioxide mixed back toward the surface, a delay that would buffer the otherwise sudden rise to worrisome levels. Herzog and others will soon perform tests, perhaps off Hawaii, to in-

vestigate how piping carbon dioxide into the deep ocean affects that realm.

Rather than sequestering carbon dioxide in the sea, other researchers argue the carbon should be returned to the ground. Many natural gas deposits already contain huge quantities of carbon dioxide. So it is unlikely that pumping in more would harm the subterranean environment. And petroleum engineers are already well versed in the mechanics of this operation. For years oil companies have taken carbon dioxide from underground deposits and injected it into deep-seated formations to aid in flushing oil from dwindling reservoirs. Although such efforts to enhance recovery normally cycle the carbon dioxide back to the surface, one could, presumably, permanently park the carbon dioxide in suitable formations (for example, depleted natural gas fields).

Some petroleum companies are banking on that premise. For example, the largest Norwegian oil concern, Statoil, is now completing an offshore facility to separate carbon dioxide from the natural gas it extracts from one field under the North Sea. Making up 9 percent of the gas there, this carbon dioxide constitutes an irksome contaminant. Rather than vent the unwanted gas, Statoil will return it to a nearby underground formation and avoid having to pay the Norwegian carbon tax on its release.

Even more dramatic plans are in the works for a huge natural gas field near the Indonesian island of Natuna. Because nearly three quarters of the gas in that deposit is carbon dioxide, the developers (Mobil, Exxon and the Indonesian state oil company) have decided that they will put this greenhouse gas immediately back underground. Otherwise, exploiting the Natuna field would add about one half of 1 percent to the carbon dioxide produced globally by the combustion of fossil fuels—an enormous contribution for a single source.

But perhaps the prime example that could serve as the template for combating global warming with sequestration comes from the Great Plains Gasification Plant. That North Dakota facility, a spin-off of the U.S. government's former synthetic fuels program, now converts coal to gas (methane), a fuel considered relatively benign because it contains less carbon per unit of energy. Carbon that was originally in the coal will soon be piped over the border to Canada as compressed carbon dioxide, to be used for enhanced oil recovery in Saskatchewan's Weyburn Field.

Such separation of carbon from coal and injection as carbon dioxide into the ground may prove especially relevant to developing nations, such as India and China, which will surely want to exploit their large coal reserves into the next century. China alone has more than 10 percent of the world's supply. But using such deposits need not transfer all that fossil carbon to the atmosphere if these countries convert the coal to cleaner fuels (methane or methanol) and sequester the leftover carbon dioxide.

Eventually, these and other countries could stop releasing carbon entirely. One idea, first advanced by Dutch workers in 1989, would be applicable to so-called integrated coal-gasification combined-cycle power plants. Wim C. Turkenburg of Utrecht University explains what he and his colleagues proposed: Oxygen added to the coal would form an intermediate gas mixture that would then be converted to hydrogen and carbon dioxide at high pressure by reacting it with water vapor. The hydrogen could be burned to generate electricity, and the carbon dioxide could be separated and sequestered underground. Turkenburg says that "the increase in production costs would be about 30 percent," whereas previous estimates for removing carbon dioxide from the flue gases of a conventional power plant had promised to double the price of electricity.

ALEX QUESADA *Matrix*

PETROLEUM FIELDS
might serve as a place to put excess carbon.

Robert H. Williams of Princeton University's Center for Energy and Environmental Studies was particularly struck by the Dutch idea: "In effect what they were doing was making hydrogen out of coal." Williams, who in 1989 had just written a book about producing hydrogen from solar energy, still looks forward to a hydrogen-based economy, but his thinking about the prospects for generating this fuel has since shifted. "For most of the next century, I think that hydrogen will be produced from carbonaceous feedstocks," Williams opines.

Producing hydrogen in that way is, in fact, going on today—and on a large scale. About 5 percent of the natural gas in the U.S. is routinely converted to hydrogen for use by petrochemical industries or for making fertilizer. Such production could presumably expand rapidly, were hydrogen ever desired to run fuel-cell-powered vehicles or electrical generating stations.

The prospects for "decarbonizing" fossil fuels are certainly promising. But the difficulties in handling large quantities of carbon dioxide safely (the gas, though nontoxic, can cause asphyxiation) and the costs of separation and sequestration will be difficult to judge until further projects test the practicality and economics of this approach. One attempt to do so may begin as early as 2001 in Norway, where a tax of $53 per ton of carbon dioxide released provides good incentive to pursue alternatives.

Such efforts, which would need to involve the oil and petrochemical industries in planning and execution, will surely blur the lines usually drawn in debates about how best to address increasing carbon dioxide and the threat of global warming. So it may take people on all sides of the issue a while to get comfortable with the notion that fossil fuels, if exploited properly, could continue to service society without threatening to change the climate. *—David Schneider*

SCIENCE AND THE CITIZEN

FIELD NOTES

EXTREME SCIENCE

Locked in an Arctic ice floe, a ship full of scientists drifts for a year

On board the icebreaker *Des Groseilliers*, the night seems eerily quiet, still and warm. There is no throaty rumble of engines, although the ship is moving. No pitch or roll, although we are floating in the Arctic Ocean just 1,000 miles from the North Pole. No biting chill, despite winds blowing outside at –30 degrees Celsius. The propellers that plowed this Canadian Coast Guard vessel into the heart of a five-mile-wide, six-foot-thick chunk of the polar ice cap stopped turning 12 days ago, on October 2. The hull is now encased in thick, azure ice on all sides. If the 50 scientists from 17 research institutions who are on board get their wish, it will stay that way until late October—of 1998.

From the air, the *Des Groseilliers* looks like a 322-foot-long Gulliver fallen in the snow, lashed by bundles of copper cable and optical fiber to a surrounding hamlet of squat huts and spindly instrument towers. It is for all intents no longer a ship but a hotel, power plant and command center for Ice Station SHEBA. The yearlong SHEBA (Surface Heat Budget of the Arctic Ocean) expedition, funded primarily by the National Science Foundation, is measuring how heat flows between sun, clouds, air, ice and ocean within a typical 39-square-mile patch of the Arctic.

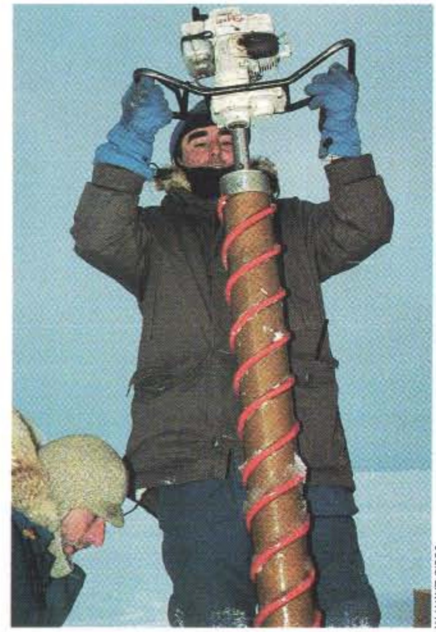
If the researchers here are successful, the data they gather will help fill embarrassing holes in the computer models that climatologists use to predict whether atmospheric pollution will lead to global warming, melting ice sheets and rising seas. And if they are lucky, none will themselves fill a hole in the ice or in the belly of a polar bear.

Such risks are quite real. "The first day we stopped on the ice, we saw a polar bear," reports Captain Claude Langis as he pans binoculars across the area from the ship's bridge. The creature fled at the sound of snowmobiles. But others may be bolder, so new arrivals are handed a brief pamphlet describing how to fire a shotgun in order to drop a bear.

The next morning Donald K. Perovich, an Army Corps of Engineers physicist and SHEBA's chief scientist, tosses a rifle onto the sled as we prepare to go to "Baltimore," one of several study areas scattered within a few miles of the ship that have been named for cities whose baseball teams made the playoffs. "The protocol for travel outside of 'town' is to take a minimum of two people, two snow machines, two radios and one weapon," he says. "A GPS receiver is handy, too; yesterday the fog rolled in while we were out there, and we couldn't see the ship anywhere."

As we stop on the way to check the load, Perovich turns and with a cockeyed grin says, "We're standing here on about six feet of ice and 11,000 feet of water. Where we're going, we will be on two feet of ice and 11,000 feet of water," he continues, extending a mittened hand toward the gray wall where the low cloud deck blends almost seamlessly into the snow hummocks. "Ready to go?" I pause to think about this.

While Perovich drills ice cores at Baltimore, his colleague Jacqueline A. Richter-Menge removes her gloves to connect sensors that measure the stress in the ice to a battery-powered recorder. Her thin fingers blanch immediately.



W. WAYT GIBBS

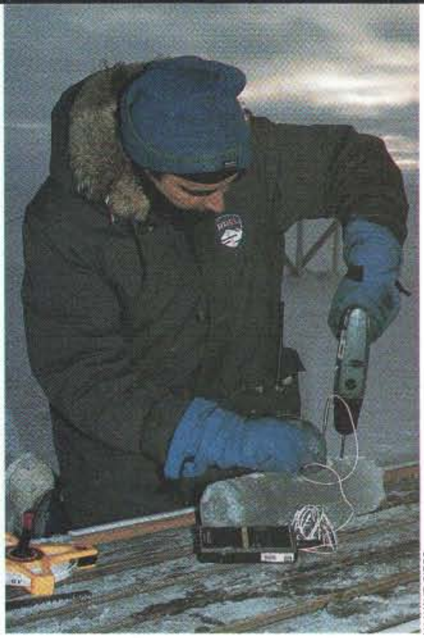
ICE PHYSICIST
Donald K. Perovich drills on two feet of ice and 11,000 feet of water.

"On another Arctic project several years ago, we set out our sensors and then came back to find that none of them were working," she says. "The Arctic foxes, it turned out, had eaten through all the cables. So now we cover them with PVC and tin cans."

Nearby, Edgar L. Andreas, another army researcher, is tending to one of

W. WAYT GIBBS

ICE STATION SHEBA,
supported by an icebreaker frozen in place just 1,000 miles from the North Pole, drew 50 scientists from 17 institutions for a yearlong climate study.



ICE CORE MEASUREMENTS, along with stress sensors, should reveal how the polar cap responds to temperature changes.

several weather stations that his atmospheric team has deployed around the floe. The machine bristles with high-tech gadgets: a Doppler wind-speed sensor hangs off one arm; on another, hemispherical radiometers face up and down to measure the solar and thermal radiation both heading for the snow and rising from it.

"Damn," Andreas mutters through the icicles dangling from his mustache as he notices heavy hoarfrost encrusting many of the instruments. "That's not good. I'm not sure what we're going to do about this frost," he sighs. "This is the first time we've used this equipment in the Arctic. At our other installations in the South Pacific and Oklahoma, we don't have this problem."

As he gingerly brushes off the crystals, I wonder how long his instruments will get such careful attention. By November, a few weeks before the Arctic sun sets for the last time until spring, Andreas, Perovich and most of the other scientists will have flown south to spend the winter with their families. The 15 technicians left behind will try to keep the hundreds of scientific instruments running smoothly through the darkness and bitter cold.

Frost, foxes and bears may be the least of their worries. On October 21 a 10-foot-wide crack fractured the main airstrip and cut off the Cleveland field site. Days later other breaks appeared between Andreas's Baltimore station and the icebreaker. Then, just after the witching hour on Halloween, the floe split into two right at the ship. A mooring line snapped and power cables were severed, shorting out several instruments.

"We will have more of this," predicts Andreas Heiberg, SHEBA's logistics chief at the University of Washington. Perhaps the project's investigators, as they lie snug in their beds, should wish for their technicians a quiet, still and warm winter's night. *—W. Wayt Gibbs on Ice Station SHEBA*

BIOLOGY

DON'T STRESS

It is now known to cause developmental problems, weight gain and neurodegeneration

Most people do not share Chicken Little's fear of falling skies. Stress is, after all, largely subjective. Nevertheless, it does prompt a series of marked physiological changes: The adrenal gland cranks out steroids that mobilize sugars and fat reserves. Additional hormones curb growth, reproduction and other nonessential activities to conserve energy. And the brain produces more epinephrine to ready the heart and other muscles for action.

In the face of danger, this short-lived reaction helps you survive. If the stress response is regularly tripped for the wrong reasons, however, it has the opposite effect. Indeed, researchers have known for some time that chronic stress often leads directly to certain illnesses, including heart disease, hypertension, depression, immune suppression and diabetes. Recently they have discovered that stress also causes developmental abnormalities, unhealthy weight gain and neurodegeneration. Fortunately, some of these new insights suggest better means for combating excess stress.

An individual's susceptibility to undue stress seems to reflect, in part, early life experiences. Michael Meaney and his colleagues at the Douglas Hospital Research Center in Montreal examined levels of corticotropin-releasing hormone (CRH)—the master hormone choreographing the stress response—in baby rats. They found that when mother rats lick their offspring often, the pups produce less CRH. "The amount of maternal licking during the first 10 days of life is highly correlated with the production of CRH in the hypothalamus of the brain of the adult offspring," Meaney says.

In addition, Meaney discovered that, compared with isolated infants, licked rats develop more glucocorticoid receptors in the hippocampus. These receptors, when activated, inhibit the production of CRH in the hypothalamus and thus dampen the stress response. Licked rats also produce more receptors for the CRH-inhibiting neurotransmitter GABA in both the amygdala and locus coeruleus, brain regions associated with fear. "When the rat is raised in calm environments, regions of the brain that inhibit CRH are enhanced," Meaney summarizes. "But bad environments enhance areas that activate CRH production. So over the long term, these systems are biased to produce more or less base amounts of CRH." In effect, early experiences set the sensitivity of an individual's stress response.

Not only do orphaned rats generate fewer glucocorticoid and GABA receptors, they actually have fewer neurons in certain brain regions as well. Mark Smith of the Du Pont Merck Research Labs and researchers at the National Institute of Mental Health looked at patterns of programmed cell death—a normal pruning process—during development. They found that in orphaned pups, twice as many cells died in several brain areas, particularly in the hippocampus, a central structure in learning and memory. Smith suggests that a lack of tactile stimulation might bring about this cell death much the way that insufficient visual stimulation causes abnormal organization of the visual cortex in infants.

Mary Carlson of Harvard Medical School observed behavioral problems in socially isolated chimpanzees and suspected that the autisticlike symptoms stemmed from a lack of tactile stimulation. So she and her co-workers chose to study the adrenal stress steroid, a glucocorticoid (GC) called cortisol, in Romanian orphans, who often display similar behaviors. Half of the children Carlson studied had participated in a social and educational enrichment program, and half had not. Compared with family-reared children, all showed retarded physical and mental growth. But the enriched children had more normal levels of cortisol during the day and under stress than the most deprived children did. Those with the most irregular

cortisol fluctuations suffered the most extreme behavioral and learning problems.

Over time, elevated levels of GCs cause other serious disorders. Studies done by Mary F. Dallman of the University of California at San Francisco indicate that persistently high levels of GCs interact with insulin to increase food intake and redistribute energy stores in the body. "The results may be very clinically relevant because sustained responsiveness of the stress program to new stimuli may be a root cause for abnormal cardiovascular events in highly stressed individuals," Dallman says. "In addition, the redistribution of energy stores from muscle to fat, particularly abdominal fat, may have a role in the development of abdominal obesity, which is strongly associated with increased incidence of adult-onset diabetes, coronary artery disease and stroke."

Robert M. Sapolsky of Stanford University has found that total lifetime exposure to GCs best determines the rate of neuron loss in the hippocampus and cognitive impairment during aging. Sapolsky reports that not only do chronically high GC levels kill off hippocampal neurons, they leave many others vulnerable to damage from epilepsy, hypoglycemia, cardiac arrest and proteins implicated in Alzheimer's disease and AIDS-related dementia. "Metaphorically, GCs make a neuron a bit light-headed," Sapolsky explains, "and if that happens to correspond with the worst day of that neuron's life, the cell is much more likely to succumb to the stroke or seizure."

Sapolsky and his co-workers are developing gene therapies to protect stress-weary neurons. But a simpler solution may come from work outside the laboratory. For 18 years Sapolsky has studied a population of wild baboons in the Serengeti. In stable hierarchies, subordinate animals have higher levels of GCs—as well as less "good" cholesterol and less robust immune and reproductive systems. The lowest levels of GCs occur in males with the strongest social networks. "These more socially savvy or socially affiliating personality styles appear to be lifelong and to predict more successful lifelong rank histories, life span and old age," Sapolsky adds. "The worst thing for an animal is to remain isolated." —*Kristin Leutwyler*

HUMAN ORIGINS

ANCESTRAL QUANDARY

Neanderthals not our ancestors? Not so fast

After researchers published the first analysis of ancient human DNA in the journal *Cell* last July, the case was closed, or so it seemed. "NEANDERTHALS WERE NOT OUR ANCESTORS" read the cover, featuring a photograph of the archetypal specimen's skullcap with its heavy, arched browridge so unlike our own relatively smooth brows. The pattern of differences between Neanderthal and modern DNA indicated to the team that Neanderthals were an evolutionary dead end, replaced by modern humans without any interbreeding. Popular accounts hailed the research as proof of a recent African origin for all modern humans, but has the long-standing debate over human origins really been put to rest? Judging from subsequent reactions among geneticists and paleoanthropologists, apparently not.

The *Cell* paper supports the so-called out-of-Africa model of human evolution put forth by paleoanthropologist Christopher B. Stringer of London's Natural History Museum. It states that modern humans originated in Africa 130,000 to 200,000 years ago and spread from there less than 100,000 years ago, replacing archaic populations such as Neanderthals all over the world. The competing hypothesis is multiregional evolution, championed by University of Michigan paleoanthropologist Milford H. Wolpoff. It holds that humans arose in Africa some two million years ago and evolved as a single, widespread species, with multiple populations interconnected by genetic and cultural exchanges.

The DNA in question, retrieved from a Neanderthal arm bone, is of the mitochondrial variety. Mitochondria—the cell's energy-producing organelles—have their own DNA and are passed on from mother to child. Unlike nuclear DNA, mitochondrial DNA (mtDNA) does not undergo genetic recombination during the cell cycle. The variation that exists between two mtDNA sequences is instead the result of mutation alone, and because mutations are thought to accumulate at a constant rate, the amount of time that has passed since two mtDNA

IN BRIEF

Bird Brains
Some bird brains are bigger than others, researchers at the University of Washington now say. Doctoral student Tony Tramontin, collaborating with psychology and zoology professors, examined the growth of brain regions that white-crowned sparrows use for singing. Previously, scientists thought that lengthening days and corresponding hormonal changes controlled the development of these regions in seasonally breeding birds. But Tramontin found that social cues held equal sway. Indeed, in male birds living with females, the brain regions grew 15 to 20 percent larger than they did in male birds living alone or with other males. It is the first observation of socially induced changes in the avian forebrain.

JOE McDONALD *Bruce Coleman Inc.*

A Quick Glucose Test
Scientists at the Mayo Clinic in Rochester, Minn., have announced that in preliminary tests, a new device for measuring glucose levels in diabetics performed as well as blood tests did. The workers tested 67 adult volunteers using a new device that collects a sample of skin fluid by way of a tiny needle. They also tested the glucose levels in these volunteers by the finger-stick method. They found that both the skin-fluid sample and the finger-stick measured the correct glucose levels with an accuracy of 97 percent.

Smart Gene
It has long been a contentious question: Do experiences or genes deserve credit for genius? Now, after more than six years of work, Robert Plomin of the Institute of Psychiatry in London reports that he has isolated the first specific gene for human intelligence. Plomin took blood samples from gifted children at a special summer school at Iowa State University and from a control group of students having average intelligence. He found that all the children with extremely high IQs also showed a high occurrence of the *IGF2R* gene, located on chromosome 6, in their DNA.

More "In Brief" on page 20

In Brief, *continued from page 19*

Novel Neurochip

Cells meet silicon in the first neurochip, invented by Jerome Pine and four colleagues at the California Institute of Technology. The group harvested neurons from the hippocampus of rat embryos and isolated them using a protein-eating enzyme. Researchers then inserted the individual cells into separate wells in a silicon chip, each of which contained a recording and a stimulating electrode. After they added nutrients, the neurons grew dendrites and axons extending out of the well and formed electrical connections with neurons nearby. The network should help scientists study how neurons maintain and alter the strengths of their connections—a process thought to be involved in memory. So far the chip fits only 16 cells. It could house millions. But Pine and his co-workers first must find better nutrients to keep the cells alive longer and a more efficient method for placing cells into the wells.

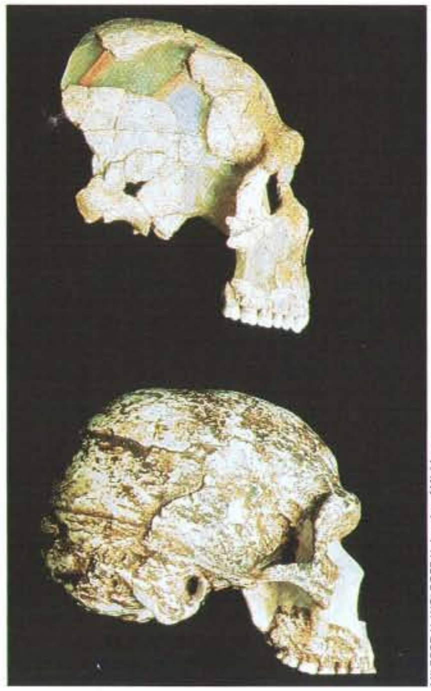
Dragging Out Space and Time

Back in 1918, physicists pondering Einstein's general theory of relativity predicted that space-time became distorted near spinning black holes, a phenomenon called frame dragging. Until recently, however, there was no proof. Because the gravitational grip of black holes lets no light escape from them, these objects are impossible to see.

JOE BERGERON Courtesy of *Sky & Telescope*

So to study them, researchers watch orbiting sister stars instead. A black hole sucks matter and gases away from these stars, which creates a swirling disk around it—like water spiraling down a drain. This matter heats up as it approaches the black hole and begins to emit x-rays. When Wei Cui and his colleagues at the Massachusetts Institute of Technology measured the variation in the intensity of these emissions, they discovered a disturbance in the matter's orbit: not only did the matter itself orbit the black hole, but its orbit, too, was wobbling around like a top. Imagine that near your sink's drain, the porcelain, as well as the water, rotated. A team of Italian physicists has reported evidence of similar frame dragging around spinning neutron stars.

More "In Brief" on page 22



MILFORD H. WOLPOFF *University of Michigan*

SEPARATE SPECIES?
Fossils of a Neanderthal from the St. Césaire rock shelter in France **(top)** ***and a modern human from Skhul cave in Israel*** **(bottom)** ***combine features typical of both groups, perhaps the result of hybridization that may support the idea that these are members of the same species.***

sequences diverged can, in theory, be calculated (although this "molecular clock" requires several potentially problematic assumptions). Researchers can then construct "gene trees" to trace the lineage of that gene.

The *Cell* authors drew their conclusions after determining that the variation between Neanderthal and modern mtDNA was on average four times greater than that found between any two moderns. In addition, the Neanderthal mtDNA did not show any special similarities to mtDNA from modern Europeans, which one might expect if Europe-dwelling Neanderthals contributed to the modern gene pool. But some researchers believe the data can be interpreted differently. Simon Easteal, a geneticist at the Australian National University, observes that chimpanzees and other primates display much more within-species mtDNA variation than humans do. Taking that into account, he says, "The amount of diversity between Neanderthals and living humans is not exceptional."

Moreover, many scientists think that too much has been made of this very short segment of mtDNA, which came from a single individual. The evolutionary history of mtDNA, a lone gene, is only so informative. "You can always construct a gene tree for any set of genetic variation," says Washington University geneticist Alan R. Templeton. "But there's a big distinction between gene trees and population trees," he cautions, explaining that a population tree comprises the histories of many genes.

In fact, examinations of modern human nuclear DNA undermine the out-of-Africa model by suggesting that some genes have non-African origins. University of Oxford geneticist Rosalind M. Harding studies variation in the beta-globin gene, certain mutations of which cause sickle-cell anemia and other blood diseases. Harding found that one major betaglobin gene lineage, thought to have arisen more than 200,000 years ago, is widely distributed in Asia but rare in Africa, suggesting that archaic populations in Asia contributed to the modern gene pool. And studies of the Y chromosome by Michael F. Hammer, a geneticist at the University of Arizona, indicate that prehistoric population dynamics were much more complicated than simple replacement. His results reflect migrations both out of and back into Africa.

Both Hammer and Harding think the overall picture emerging from the seemingly inconsistent genetic data best fits one of the "intermediate" models of human evolution, such as the assimilation model engineered by Northern Illinois University paleoanthropologist Fred H. Smith. According to Smith's model, the patterns visible in the fossil record suggest that both expansion out of Africa and genetic interchange among populations were at work.

But Wolpoff remains convinced that the multiregional evolution hypothesis best explains the pattern and process of human evolution (including the shared features of the fossil skulls shown above); he contends that these middle-ground models can be subsumed under multiregionalism. In fact, he questions whether the evolutionary fate of Neanderthals is important at all in terms of the broader issue of human origins. One would have to demonstrate replacement of archaic populations all over the world to disprove his model, he asserts.

Clearly, the arguments have not been resolved. But as data from ancient and contemporary sources accumulate, the new millennium may witness the answers to age-old questions about our extended family history. *—Kate Wong*

***In Brief**, continued from page 20*

New Moons

Astronomers first sighted two new moons—temporarily named S1997 U1 and S1997 U2—orbiting Uranus last September, and the finding was confirmed by Halloween. Philip Nicholson and Joseph Burns of Cornell University, Brett Gladman of the University of Toronto and J. J. Kavelaars of McMaster University discovered the objects, which trace an irregular path around the distant planet, using the five-meter-diameter Hale telescope. They are the faintest satellites ever seen from the ground and are estimated to be a mere 80 and 160 kilometers in diameter. With these additions, Uranus now has a total of 17 known circling moons.

Chimerical Concertos

Is it possible to compose a faux Mozart symphony that sounds enough like the real thing to fool even sophisticated musicologists? David Cope of the University of California at Santa Cruz and his computer have done just that. Cope's system, dubbed Experiments in Musical Intelligence (EMI), breaks down sample scores into a series of small "events." Next, it determines how these fragments fit together to form a musical grammar of sorts. When the program then modulates the fragments and mixes them back together, the resulting music has the same style as the original. Fed Mozart, EMI can identify about 40 recurrent flares, including favored rhythms and orchestrations. And EMI has identified similar musical signatures for several other composers.

ALAIN BENAINOUS *Liaison International*

Baffling Birth Defect

During the past 20 years, the prevalence of hypospadias—a condition in which the urinary opening on the penis is in the wrong place at birth—has nearly doubled. And no one knows why. The Centers for Disease Control and Prevention reported in *Pediatrics* last November that the rate of the defect had soared from 40 cases in 10,000 births in 1970 to 79 cases in 10,000 births in 1993. The condition—which is thought to result from an insufficient testosterone surge nine to 12 weeks after conception—can be surgically corrected, and the earlier it is done, the better.

—Kristin Leutwyler

ANTI GRAVITY

Tender Is the Bite

John Long hails from a time when nonspecialists did lots of varied and interesting science. He was a meteorologist during World War II. In the late 1940s he engineered robots ("We used to call it remote-control equipment," he says) to handle radioactive metallurgy for Glenn T. Seaborg's work discovering new elements and later started his own business developing those robots. In the late 1950s he went to Lawrence Livermore National Laboratory, where he remained for the rest of his official career in nuclear weapons design. There Long discovered that conventional weapons were superior at tenderizing meat.

Long worked with an experimental setup that called for a small conventional explosive to be detonated underwater, creating shock waves. A wire needed to be replaced in the setup after each explosion. Long wondered what would happen if some snakebit technician stuck his hands in the water to change a wire that was still good and was subjected to an accidental explosion. "I got to thinking, 'Gee, the shock wave is just going to travel through the flesh—it would probably be fatal,'" Long recalls by telephone last November 3, his 78th birthday.

He also wondered how a hunk of beef might be affected by that same shock wave. Armed with C-4 (that puttylike explosive movie heroes are always jamming onto the sides of tanks and vault doors), a slab of meat and a dream, Long ran some tests. As in any engineering problem, the first run uncovered some bugs: "We couldn't find the meat after," Long admits. The next try included a large piece of tough rump and a more suitable explosion. The blasted meat, when subsequently barbecued, was as "tender as one of the good steaks you'd buy for $10 in those days," Long says.

Back then, meat processors shipped entire sides of beef, with bones, to butcher shops and supermarkets. The sides would hang in warehouses to tenderize via aging and the odd Rocky Balboa workout. Shock waves to whole sides of beef failed, Long found, because bones altered the characteristics of the wave and left the meat tough in some parts, pulpy in others. Long put his idea on ice, and only lazy fishermen bombed the waters in search of a decent meal. (Fishin' bombs are unconventional but nonnuclear.)

Times change. If they ever make *Rocky VI*, Sylvester Stallone will be mixing it up with big blocks of boneless meat, today's preferred shipping form. That might look as strange as placing a big, bagged block of meat into water and letting loose with a small explosion. But that is just what has been going on at the meat labs of the U.S. Department of Agriculture, in tests of what Long now calls the hydrodyne process. "Three years ago a lot of people laughed. They thought this was funny," says Morse B. Solomon, the USDA's chief meat scientist, about

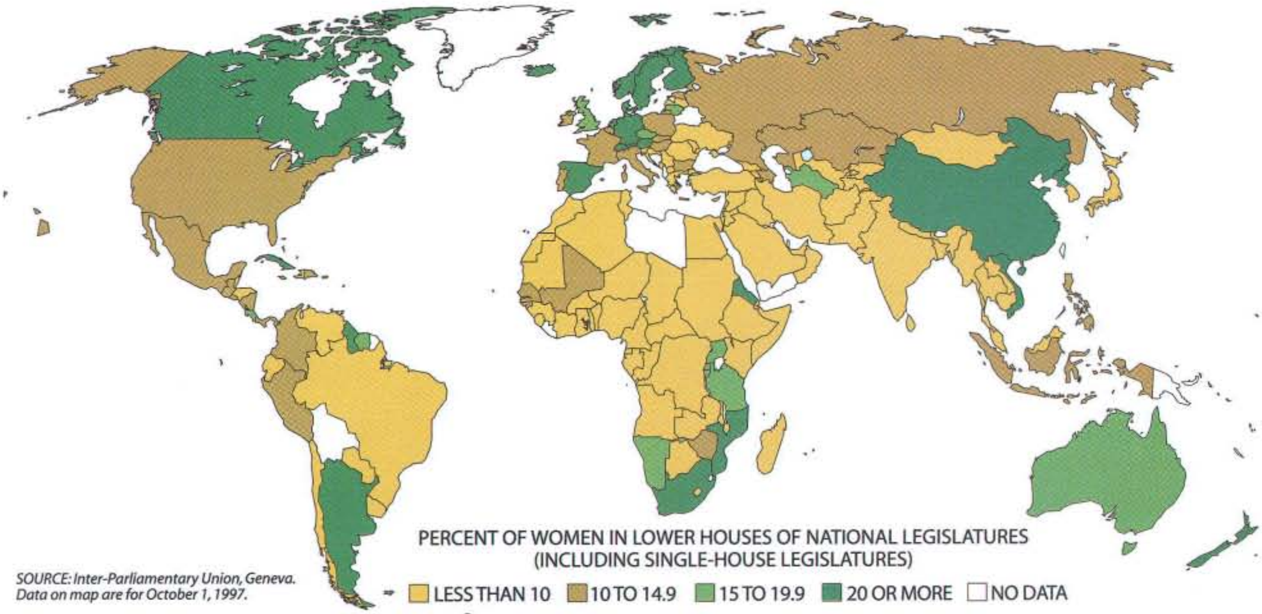
MICHAEL CRAWFORD

Long's beef bombings. "They're not laughing anymore. Now they're asking, 'When is this going to be available?'"

They're asking because the shock waves cut tenderization time from a month to less than a second. And because the process, still being fine-tuned, even seems to work on tough, low-fat cuts. Electron microscopy shows that the shock wave causes tiny tears in the tissue that keeps muscle fibers orderly—the resulting relaxation probably explains the tenderization effect. Flavor, like the fats and oils mostly responsible for it, seems unaffected. The waves also appear to kill at least some of the bacteria that eventually spoil meat; therefore, the method might increase storage life. The wisdom of Solomon thus has it that the hydrodyne method could be commercialized by the end of the year. If the lasting application of nuclear weapons research turns out to be better steaks, it will have been worth the wait for Long.

—Steve Mirsky

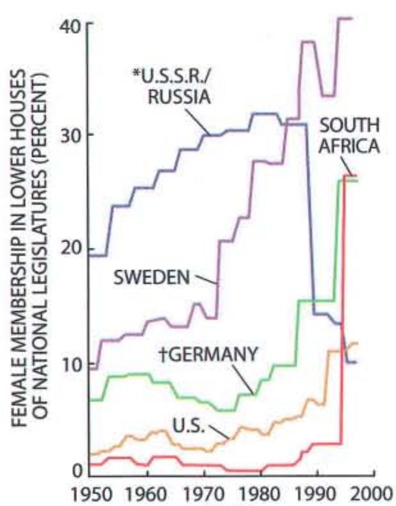
Women in Politics throughout the World



SOURCE: Inter-Parliamentary Union, Geneva. Data on map are for October 1, 1997.

The markedly uneven participation of women in public life is illustrated by the map, which shows the proportion of female-held seats in national legislatures. Data are shown only for lower houses or for single houses in the case of those countries that have no upper house. Lower houses of legislatures, as in the U.S. and the U.K., are generally more representative of the electorate.

Women's participation in the national legislatures of Western democracies has been growing since the end of World War II, slowly in some places, such as the U.S., and dramatically in others, such as Sweden. In the U.S., France, Italy and Ireland, 12 percent or less of lower-house seats are now held by women, whereas in other places, such as the Nordic countries, Germany and the Netherlands, women hold more than a quarter of the seats. These differences reflect sharply divergent cultural traditions, such as the American tendency toward conservative religion, which has a traditional view of women's roles. Americans emphasize freedom at the expense of equality and so tend to neglect economically disadvantaged groups, such as women and blacks. On the other hand, Scandinavians and others have traditionally put social justice for groups ahead of economic freedom for individuals. Other factors promoting women's participation are proportional representation (losing parties still get to send delegates) and a parliamentary, multiparty system, both of which exist in Sweden, where each of seven parties won substantial blocks of votes in the 1994 parliamentary elections.



**Soviet Union until 1991, Russian Federation thereafter*
† West Germany until 1989, united Germany thereafter

In recent decades women candidates have tended to fare better under left and center-left regimes. The 1997 increase in female-held seats in the British House of Commons occurred with the return to power of the Labour Party after 18 years of Conservative rule, whereas the increase in Sweden happened largely during the tenure of the Social Democratic Labour Party and its allies. There are exceptions to this rule, as in the case of Germany, where women have gained seats during the moderate conservative rule of Helmut Kohl (*chart*).

A significant exception to the general trend of increasing female participation in politics is eastern Europe, where under communism women made up 20 to 35 percent of the lower houses. But the coming of democracy brought a male backlash. (As one Polish official put it, "The ideal must still be the woman-mother, for whom pregnancy is a blessing.") Women's participation in legislatures has fallen by half or more in Poland, Bulgaria, Hungary, Romania and the former Czechoslovakia. In Russia, participation is down by two thirds as compared with that in the former Soviet Union (*chart*).

With the exception of communist regimes, Asian, African, Latin American and particularly Arab countries tend to have low female participation rates in national legislatures, reflecting, in part, traditional attitudes. Important exceptions are South Africa, where the government of Nelson Mandela is committed to the promotion of women's rights, and Argentina, where by law 30 percent of those on party-candidate lists must be women. —*Rodger Doyle (rdoyle2@aol.com)*

RODGER DOYLE

PROFILE

From Naked Men to a New-World Order

Finding a hidden logic in "primitive" myths made Claude Lévi-Strauss the most renowned anthropologist alive

Outside Claude Lévi-Strauss's office building in the Latin Quarter of Paris, chaos rules. Amid a haphazard jumble of institutes, bookshops and cafés, mopeds and improbably tiny cars weave through the narrow streets, dodging knots of university students, all of whom seem, like myself, to be five minutes late for some crucial appointment.

Inside the Laboratory for Social Anthropology, the sense of order is palpable. As I climb the stairs to a mezzanine office, each step seems to lead not only up in space but also back in time. The door to the office opens, from all appearances, into the 19th century. Here, in his isolated aerie adorned with enclosed bookcases and exotic curios beneath bell jars, Lévi-Strauss is perched at an antique desk. As I apologize for my tardiness, he looks at me quizzically, as if time is irrelevant, and moves over to his picture window overlooking the regiment of oversized file cabinets that nearly fill the laboratory below. Crowning them on the far wall is an ornate arching banner inscribed *Pour la Patrie, les Sciences et la Gloire*—For the Fatherland, the Sciences and the Glory.

It is a fitting motto. This, after all, is a man who reshaped the world's opinion of primitive societies largely through his work not on some remote Pacific island but behind a desk in Paris. Who shoved cultural anthropology toward a more formal method and more scientific aspirations. Who inadvertently ignited an intellectual fad that swept through nearly all the humanities and made him, as American writer Susan Sontag put it, the first "anthropologist as hero."

RAPHAEL GAILLARDE *Gamma Liaison Network*

IN HIS ELEMENT, Claude Lévi-Strauss ponders "the savage mind."

Yet for all the glory heaped on Lévi-Strauss in his 89 years—inclusion in the French Legion of Honor, the Academie Française and the U.S. National Academy of Sciences; honorary doctorates from 11 universities, including Oxford, Yale and Columbia; a chair created just for him at the exclusive Collège de France—the motto fits best in another, more idiomatic sense of *pour la gloire:* "for the intellectual challenge."

Lévi-Strauss maintains that he was made for structural analysis, the technique he championed as a tool for discovering fundamental constants of human nature buried within the vagaries of myths and rituals—that it is simply the way he entertains himself. As a preliterate child, he recounts, he boasted that he could read because he had noticed that the pattern "bou" appeared on the signs for both the butcher (*boucher*) and the baker (*boulanger*). Later, during school vacations, he hiked along the flank of limestone plateaus in the Cévennes Mountains. "I would try to discover the contact between two geological layers and follow it despite obstructions," he says. "It was a game."

Undergraduate studies in law and philosophy failed to exercise this talent and bored the restless Lévi-Strauss. He turned to politics for entertainment, leading two socialist student groups. Despite his disinterest in school, the distractions and the severe gastrointestinal distress that ensued after he swallowed a vial of narcotics given him as a pick-me-up before his final oral exam, he graduated third in his class. "I appeared before the jury looking like death," he recalled in a 1988 interview, "without having been able to prepare a thing, and improvised a lecture that was considered to be brilliant and in which I believe I spoke of nothing but Spinoza." (The topic was applied psychology.)

In 1935 Lévi-Strauss set sail for Brazil and a teaching job at the University of São Paulo. During breaks, he ventured inland to record ethnographic observations of Caduveo and Bororo Indian tribes. Several years later, after quitting the university, he led a second, yearlong expedition to study the Nambikwara and Tupi-Kawahib societies.

The onset of war cut short his travels. But even before he was drafted, Lévi-Strauss had begun to realize that fieldwork was not his calling. "I enjoyed it tremendously," he says, "but the time it costs and the slowness of the results were too much for me."

So when Lévi-Strauss fled to New York City to escape the Nazis (his

grandfather was a rabbi), he began work at the New School for Social Research on a more theoretical sort of anthropology. "I prefer it because it requires less contact with fellow human beings!" he exclaims with a flash in his dark eyes. There is no doubt that is true—indeed, Lévi-Strauss has always labored alone—but theoretical work also offered the appealing opportunity to hunt once again for order within chaos.

The puzzle was the wilderness of seemingly arbitrary rules governing marriage and kinship in human societies. A solution appeared to Lévi-Strauss in the form of Roman Jakobson, a Slavic linguist also exiled to New York. Jakobson, building on the theories of Ferdinand de Saussure, had worked out a new way to analyze human languages.

The principles were simple enough. The sounds of speech have no inherent meaning, de Saussure had observed: "oo" occurs in "soothe" and "cool" but also in the French word *coup* ("a sharp blow"). Languages work because they have structure, rules that allow some combinations ("soothed") and forbid others ("soothd"). More critical, Jakobson argued, all languages share certain structures, such as oppositions between vowels and consonants, that develop independently and are passed on unconsciously. Discover the common threads, the thinking goes, and you discover something profound about the human mind.

Lévi-Strauss's great leap was to apply the same kind of structural analysis to the kinship systems of several primitive societies. In an ambitious four-year study, he focused on how each tribe's marriage rules affected the way that women were exchanged and alliances were formed. From this perspective, he claimed, a simple set of oppositions—between sibling and spousal relationships, for example—emerges to create a common structure, a "language" of kinship. Each society's marriage and kinship customs were different expressions, like sentences, of that language.

Excited by the power he perceived in this new method, Lévi-Strauss tried applying it to totemism, the practice of associating people with animals or spirits. Again he uncovered provocative patterns beneath what had looked like a meaningless jumble of irrational beliefs. Flushed with success, he began his masterwork: a structural analysis of 813 Native American myths, plus more than 1,000 variants of them, that would produce the four weighty tomes of *Mythologiques* (*The Logics of Myth*).

Painstakingly dissecting each myth into its smallest plot points, Lévi-Strauss then looked for binary oppositions and built models or drew diagrams to represent their relationships. He formulated mathematical transformations that he claimed connected a myth of one society to myths told in other societies separated by great stretches of time and distance. "Although myths appear to be absurd narratives," he concluded in *The Naked Man* (the final volume of his tetralogy), "the interconnections between their absurdities are governed by a hidden logic"—a logic, he wrote elsewhere, that "is as rigorous as that of modern science." The natives of the New World were not irrational; they simply applied their reason to different subjects than Europeans did.


COURTESY OF CLAUDE LÉVI-STRAUSS

A NAKED MAN: Lévi-Strauss among the Nambikwara of Brazil in 1938.

Although most anthropologists would now agree with that conclusion, debate still rages over the validity of Lévi-Strauss's methods. Many critics have charged that Lévi-Strauss spent too little time in the dirt to appreciate just how messy societies and their myths really are. These doubters suspect his transformations of being a bit too orderly, and their skepticism is only fed by the speed with which "structuralism" was adapted to analyze everything from novels to circus culture to *Star Trek*.

Lévi-Strauss throws up his hands when reminded of this. "This alleged structuralism [in literary criticism] is in fact only an excuse for mediocrity," a way to make uninteresting works seem important, he grumbles. Yet his own recent book, translated into English last year as *Look, Listen, Read,* casts a structuralist's eye on painting, music and poetry.

Perhaps there is meaning in this contradiction. The anthropologist who was once a hero now holds more sway over the humanities than his own field, which, he fears, has descended into internecine warfare. "It is quite popular in the United Kingdom to criticize and reject old masters," he complains. "This happens periodically in the history of any scientific discipline. But science should progress by incorporating past evidence into the new and not rejecting it."

He has begged the question, so I ask it: Is cultural anthropology truly science? After all, Lévi-Strauss, with characteristic modesty, has often claimed to have scientific goals but unscientific methods. He closes his left eye and squints at some unseen structure in the infinite theoretical space that apparently occupies one corner of the ceiling. "If I compare structuralism with the hard sciences," he answers, "I would put it at the scientific level of the Renaissance. In the natural sciences the physiologist does not criticize the zoologist for studying groups of animals [or] the molecular biologist for studying cells. In the so-called social sciences," he laments, "we are still discussing whether it is right to be either a physiologist, a zoologist or a molecular biologist!"

For better or worse, no anthropologists now wish to be structuralists. Lévi-Strauss founded no school, trained no successors. "We took some of his ideas and traveled with them in other directions," says Barbara H. Tedlock, former editor of *American Anthropologist.* "But no 'ism' dominates the field any longer."

Of course, anthropologists are used to seeing the objects of their study flicker and vanish. Faced with the extinction of his invention, Lévi-Strauss maintains, "I don't really care at all. It was the way of making sense of this data that was most coherent with my mind, that's all. I did it because I loved it." *Pour la gloire.*

—W. Wayt Gibbs in Paris

EMBRYOLOGY

OFF WITH ITS HEAD!

Headless frog embryos are here. "So what?" biologists say

In the wake of a British biologist's assertion that he had created frog embryos that failed to grow a head, many of the alarmed pronouncements that made their way into the popular media seemed to have been informed by the weirder veins of pulp science fiction rather than by scientific plausibility. Press reports conjured up imagery of human organs growing in bottles and even mutant human "organ sacks" grown from headless embryos and kept alive artificially for the sole purpose of storing organs for harvesting and transplantation. At about the zenith of surreality, a former director of the National Institutes of Health reportedly noted on the *CBS Evening News* that a headless embryo would "have zero potential to say no."

Many biologists and ethicists, however, are far more troubled by the flights of morbid fantasy, which they say could have a chilling effect on potentially beneficial research. Some were also disturbed by what they perceive as the role of Jonathan Slack, a developmental biologist at the University of Bath, in fostering the wild speculation. "Slack unleashed a torrent of silliness at the expense of the scientific community," charges Arthur Caplan, an ethicist at the University of Pennsylvania. Slack declined to be interviewed for this article.

The furor began last October 19, when the London *Sunday Times* broke the news of Slack's achievement. By controlling signaling proteins known as fibroblast growth factors, Slack altered embryonic processes that are instrumental for the growth of the head, or of the trunk and tail, of the frog *Xenopus laevis*. He was therefore able to grow not only embryos with no head but also ones that were nothing but a head. The embryos were not kept alive beyond about three days, at which point an embryo has only precursors of most of the organs and has not yet begun to feed.

In his interviews with the local press, Slack observed that no biological principle would keep a technique similar to his from working on a human embryo. Thus, he said, it was time to ponder the possibility of a headless human, cloned and grown for the express purpose of providing any needed vital organs for its anatomically complete genetic donor. "You can't stop things once they start, and it is sensible to talk about it now," he told the *Daily Telegraph*.

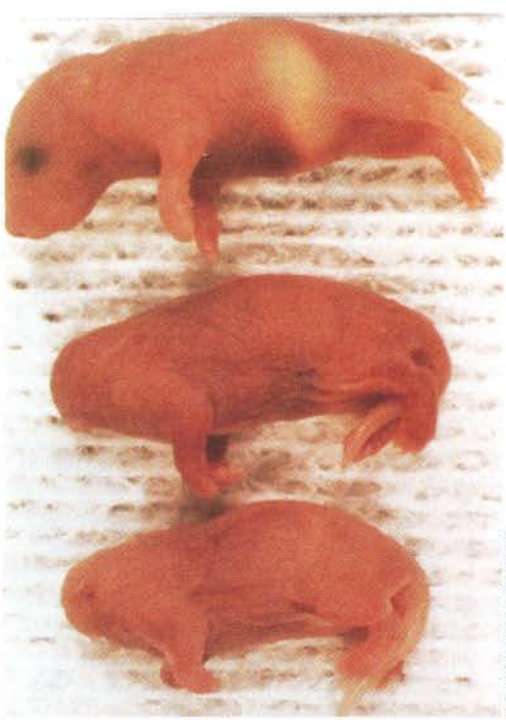
Media coverage quickly converged on what one biologist labeled the "yuk factor," with some ethicists and clergy members expressing horror and disgust. Biologists, on the other hand, were baffled by the outpouring of indignation. Genetically created headless embryos are not at all new. Headless frog embryos have been made by various pseudogenetic techniques since the early 1990s. And in 1994 headless mouse embryos resulted from studies of a gene known as *Lim1* by William Shawlot and Richard R. Behringer of the M. D. Anderson Cancer Center in Houston. Second, legal restrictions in most of the developed countries prohibit the growth outside the womb, beyond a short period, of human experimental embryos.

Perhaps most important, the technical difficulty and impracticality of the scenario outlined by Slack, in comparison with other biotechnological approaches now being explored, essentially rule it out as a source of organs for transplant any time in the foreseeable future. According to Behringer, the idea of developing Slack's technique into something that could be used with humans is "a complete fantasy. I can't understand where this is coming from."

"To get it to work in humans," explains Brigid L. M. Hogan, a cellular biologist at Vanderbilt University Medical Center, "you would have to implant the partial embryo back into a woman, and no one would want to do that." Alternatively, it might be possible to culture embryos using some kind of artificial life-support system that could nurture the embryo for perhaps a couple of months, until rudimentary organs had been formed. Versatile cells known as stem cells could then conceivably be taken from these organs and used to repopulate and repair the corresponding damaged organ in a human. The only technical problem is that the life-support system called for in this scenario is far beyond current technology. "I cannot tell you how dopey it is, physiologically or cost-wise," Caplan declares.

In the meantime, Caplan and other ethicists worry that potentially valuable offshoots from embryological research could be precluded if the public becomes overly exercised about the lurid science fiction. "We should not permit the nightmare visions to impede research now," says ethicist Ronald M. Green of Dartmouth College. "Research on cell differentiation and the genetics of embryological development [has] great potential benefits." For example, a rare genetic disorder in humans called anencephaly can partly or completely block the development of the brain and head; it is possible that work such as Slack's could shed light on the condition—and its possible prevention.

"There's an impulse to prohibit, prohibit, prohibit," Green says. "We don't even know what we're prohibiting yet." —*Glenn Zorpette*



M. D. ANDERSON CANCER CENTER

HEADLESS MICE *resulted from studies of the* Lim1 *gene in 1994 but did not cause the stir headless frogs did.*

DEFENSE POLICY

LASER SHOW

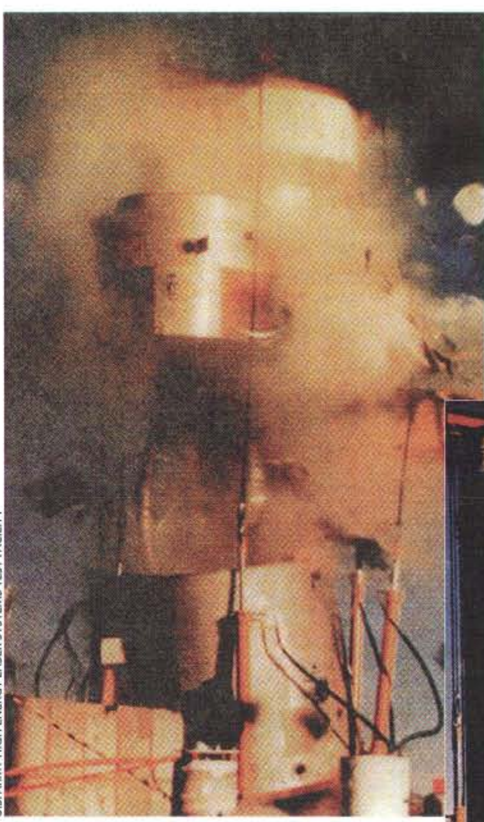
Critics charge that the Pentagon's antisatellite laser test could set a dangerous precedent

In early October U.S. Defense Secretary William S. Cohen announced he would allow the army to fire a massive laser beam at an aging air force tracking satellite 260 miles above the earth. The Pentagon emphasized the defensive nature of the test by stating that the main goal was to gather data about the vulnerability of U.S. satellites to laser attacks.

Few were convinced. For years the army believed its Mid-Infrared Advanced Chemical Laser (MIRACL) at the White Sands Missile Range in New Mexico had the potential to disable satellites, but a congressional ban kept the service from testing the hypothesis. After a Republican-led Congress let the ban drop, however, the army proposed a test of MIRACL's ability to "negate satellites harmful to U.S. forces." Only after extensive press coverage and congressional criticism did the Pentagon announce the emphasis of the test had shifted from antisatellite (ASAT) experimentation to the assessment of the vulnerability of the air force target satellite, which had been selected because it could report back on any damage from the laser. After several mishaps, the army fired at the target satellite in late October; problems with both the laser and the satellite, however, kept the Defense Department from attaining much data.

The test failure did little to settle the controversy. "Although the Pentagon is spinning the tests as a way to measure U.S. satellite survivability, most arms-control analysts would describe them as a major step forward in developing an antisatellite weapon," says Senator Tom Harkin of Iowa. "These are the same type of tests that I and others in Congress objected to years ago."

For the Pentagon to approve the test was a significant leap. Antisatellite projects have not fared well in the Clinton Defense Department and have been kept alive largely because of congressional appropriations. Moreover, critics charge, the Pentagon lacks any clear policy on ASAT weaponry, although one is in the works. "The Congress, the White House and the Pentagon have to have a serious discussion of our nation's antisatellite weapons plans before we go down the road of testing these weapons. We simply have too much at stake," Harkin remarks. As it is, he adds, "these laser tests are both unnecessary and provocative."



U.S. ARMY HIGH ENERGY LASER SYSTEMS TEST FACILITY

***TEST OF THE MIRACL LASER** was done on a Titan missile stage, which before exploding dimpled just above the halfway point, where the laser hit* (inset).

With House Minority Leader Dick Gephardt of Missouri and other opponents, Harkin believes a test of the MIRACL laser now would only incite other countries to speed development of their own antisatellite weapons and bolster the protection of their satellites. Further, argues Federation of American Scientists analyst John Pike, potential enemies probably will not even build their own reconnaissance satellites. For imagery, smaller nations such as Iraq and North Korea might rely on more technologically advanced countries (such as France, Russia, Israel and India).

In that case, the U.S. would be left with one unsavory option—the "wholesale destruction" of allies' imaging satellites, Pike notes. Taking such drastic action, "on the off chance that one of these countries might be slipping an adversary a few pictures on the side, does not seem a terribly plausible prospect or a compelling military requirement," he adds.

For the U.S. military, however, space is integral to its plans. Supporters of ASAT weapons maintain that having a proved means of disabling a satellite will discourage other countries from relying on them too heavily. Frank Gaffney, a former Reagan administration Pentagon official and ASAT supporter, contends that successful ASAT testing should give the military "confidence that it can control the use made of space by future adversaries."

For Pike, however, the laser test serves a dangerous motive. "A simple mathematical calculation demonstrates that it could destroy a spy satellite in low earth orbit, and no further proof is needed," he declares, adding that ASAT tests "will establish little beyond the legitimacy of attacking satellites."

—Daniel G. Dupont in Washington, D.C.

SEMICONDUCTORS

NEW SILICON TRICKS

Carbon could boost the speed of silicon chips

For decades chipmakers have operated on the simple premise that smaller is better. But as silicon transistors continue shrinking to the tiniest of dimensions—reducing the distance electrons have to travel and thus speeding up calculations—problems such as current leakage become acute.

Looking for a different way to add zip to silicon, scientists have been working with variations of the material that could conduct current faster. The latest: adding carbon to a mix of silicon and germanium. Various research centers, including Princeton University, the Insti-

tute for Semiconductor Physics in Germany and the University of Texas at Austin, have used carbon to fabricate transistors of reasonable circuit sizes that could lead to silicon-based chips operating in the gigahertz range—some 1,000 times faster than they do now. "We've been trying to teach an old dog new tricks," says James C. Sturm, director of Princeton's Center for Photonics and Optoelectronic Materials.

Actually, the tricks aren't so new. They rely on a 1950s idea to build electronic devices by joining different semiconductor materials of just the right compositions. At the junctions of such materials, electrons tend to speed up. Of the various semiconductor materials, the pairing of silicon-germanium and plain silicon had held great promise.

The problem, though, has been that fabricating devices from such materials has proved devilishly tricky. The main drawback has been that the natural crystal lattice of silicon-germanium is slightly larger than that of silicon, which results in strain when the two materials are layered one atop the other. Adding carbon can reduce that strain, because its atomic size is smaller than that of silicon and germanium. As a result, the overall lattice of the resultant compound is reduced and matches that of silicon more closely.

Though preliminary, the carbon research has already piqued interest in the industry. Alcatel is considering using silicon-germanium-carbon technology developed at France's Institute of Fundamental Electronics (IEF) for optoelectronic applications. The Semiconductor Research Corporation, a consortium that includes industry heavyweights Intel, Motorola and Texas Instruments, recently agreed to fund work at the University of Texas Microelectronics Research Center (MRC).

Still, despite industry enthusiasm, the new compound has brought its own share of problems. For one thing, carbon and silicon do not mix well. "Carbon's not that happy in that lattice," Sturm notes. To accommodate the uneasy union, researchers have had to resort to specialized laboratory processes to build the devices. To date, no one has found a simple, magic recipe that could work in a standard industrial setting. "Complementary approaches are needed," says Daniel Bouchier, a researcher at IEF.

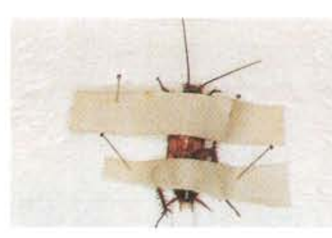
The long-term reliability of the new devices is another issue. "People have to test them and see whether they can hold up under operating conditions for extended periods," concedes Sanjay K. Banerjee, associate director of MRC.

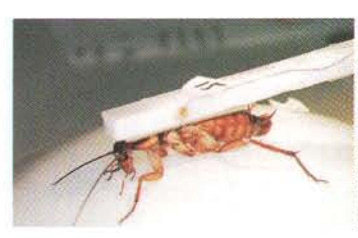
Finally, some researchers, particularly those who have learned to work around silicon-germanium's inherent difficulties, question whether the added carbon is worth the effort. Indeed, IBM has already begun shipping commercial silicon-germanium parts—for example, a two-gigahertz chip for wireless communications. IBM research fellow Bernard S. Meyerson claims that 200-gigahertz parts are entirely possible using the same technology. "We are nowhere near the limits of silicon-germanium at this time," he asserts. *—Alden M. Hayashi*

ROBOTICS

Roaches at the Wheel

Researchers in Tokyo received some notoriety last year when they showed how implants could govern the movements of a cockroach—the idea being that such roboroaches could be used for covert surveillance or for searches through wreckage. Now one engineer has worked the flip side of that relationship: a robotic vehicle controlled by a cockroach.





PHOTOGRAPHS BY HAJIME OR

Hajime Or built what he calls a "biomechatronic robot" while working on his master's degree at the University of Tokyo last year. After taping down an American cockroach (*bottom left*), he inserted fine silver wires into the extensor muscles of the hind legs. The roach was then allowed to run on what amounts to a trackball (*bottom right*). The wires picked up the weak electrical signals generated by the muscles, and the signals were amplified and fed to the motorized wheels. In this way, the machine would mimic the speed and direction the cockroach ran.

What good is a robot that tries to scurry into a crevice when the kitchen lights go on in the middle of the night? Actually, Or designed his robot to see if a biological nervous system could serve as a control mechanism. The problem for roboticists—in particular, those whose inventions emulate arthropods—is integrating and coordinating all the information needed for the legs to work together. "The fundamental issue is how to get a robot to show the agility and speed that an insect has," says Fred Delcomyn, a biologist at the University of Illinois who works on six-legged robots.

Whether Or's approach is the answer is too premature to say. For his part, Or thinks insect nervous and sensory systems could be inexpensive alternatives to sophisticated control computers that might be needed for space missions. He plans to enter a Ph.D. program in the U.S. this year and refine his roach-controlled robot. His next step? "Reduce the size of the robot so that it is similar in size to its 'driver,' " he remarks. *—Philip Yam*

CYBER VIEW

Wearing Your Computer

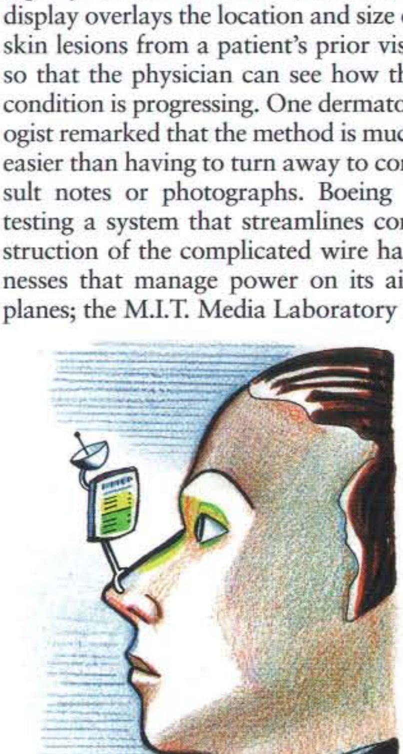
Ever since the word was first used in 1960 to describe how machines could enable humans to survive hostile environments, cyborgs have lived with us in science fiction. For instance, *Star Trek* presented a blind character who "saw" via a sensor array embedded in her clothing. Such vision may not be far off, as shown in three days of demonstrations of wearable computers held at the Massachusetts Institute of Technology last October.

Items included jewelry that flashed in time with your heartbeat, a musical jacket with a keyboard near the breast pocket and digital versions of the mood ring: Rosalind W. Picard, a researcher studying "affective computing," embedded sensors in earrings and Birkenstock sandals to identify and respond to the emotional states of the wearer. More than just a nerd playland, the conference suggested how wearable computers have uses that, despite some appearances, go beyond mere entertainment.

There are two problems that wearable computers are intended to solve. The first is finding ways to embed computers so that they can boost human abilities. One M.I.T. team is using a cap-mounted camera to capture American Sign Language for translation into synthesized speech. The second, and more common, problem is the simple frustration that your computer is never around when you need it. (Portable alternatives, such as personal digital assistants, lack the processing might of computers.) That is why conference organizer and M.I.T. student Thad Starner roams the campus with a laptop strapped to his side, a display on his head and a round, fat, key-laden chunk of plastic on which he types one-handed. "I just wanted a better brain," he explained.

Considering the cumbersome nature of Starner's approach, it is no wonder that everyone is trying to slim things down. Boston start-up MicroOptical has replaced those gawky, strap-mounted LCD screens with a tiny, mirrored cube set into one lens of an ordinary pair of eyeglasses and a small box clipped to one earpiece. Although they are still a bit clunky for everyday wear, these kinds of displays would be acceptable for industrial applications, especially those that already require safety goggles.

Several groups are testing similar reality-augmenting devices. For example, the University of Rochester is developing a system in which the head-mounted display overlays the location and size of skin lesions from a patient's prior visit so that the physician can see how the condition is progressing. One dermatologist remarked that the method is much easier than having to turn away to consult notes or photographs. Boeing is testing a system that streamlines construction of the complicated wire harnesses that manage power on its airplanes; the M.I.T. Media Laboratory is



DAVID SUTER

developing a system for training (it has one for billiards that draws lines on a pool table indicating the best shots).

Daily life is harder to accommodate: many people won't even wear glasses. But people do wear watches, clothing and jewelry. An impressive project, funded in part by the Defense Advanced Research Projects Agency, is the Sensate Liner for Combat Casualty Care. It is a cotton T-shirt woven with a mesh of electrically and optically conductive fibers and has circuitry, acoustic sensors and piezoelectric film gauges intended to collect and transmit such data as the direction and speed of a bullet striking the wearer. The goal: better triage.

The Media Lab is also experimenting with conductive fabrics. It has discovered that you can embroider keyboards onto ordinary clothing using commercial conductive thread made of Kevlar and stainless steel. Then it's a small step to attach diminutive sensors and chips.

This kind of technology could lead to convenient automation when coupled with another Media Lab project: retrieving power during walking via the shoes. It could be used to generate a low-power field that functions as a personal-area network around the body. The coupling of projects could give the world underwear that communicates directly with the living-room thermostat.

Is this the fourth wave of computing, after mainframes, minicomputers and personal computers? These folks seem to think so, and in many ways it makes sense, particularly for the medical uses that the Media Lab's Michael Hawley expects to be the first drivers of this technology. Still, the most likely outcome is that a lot of the work won't be used the way its inventors think it will. One project calls for digitizing everything from colors (output as sound) to emotions (output as bar graphs for the moment); the idea is to help teachers identify remote students' states of mind. It's hard not to think that only a geek would want automated bar charts rather than relationships with students who feel comfortable enough to type in, "I am confused." But if such a system is accurate, might it be useful in helping people whose emotions are inaccessible through illness?

We have to hope so, because most of the wearable vision seems isolationist. One set of underwear controlling the thermostat is fine; what about 1,000 sets fighting over one auditorium thermostat? Or when your shirt broadcasts your medical data? Will authorities ban color-changing clothing in banks to prevent would-be robbers from making a switch or make it illegal to turn off your cap-cam at the scene of a crime?

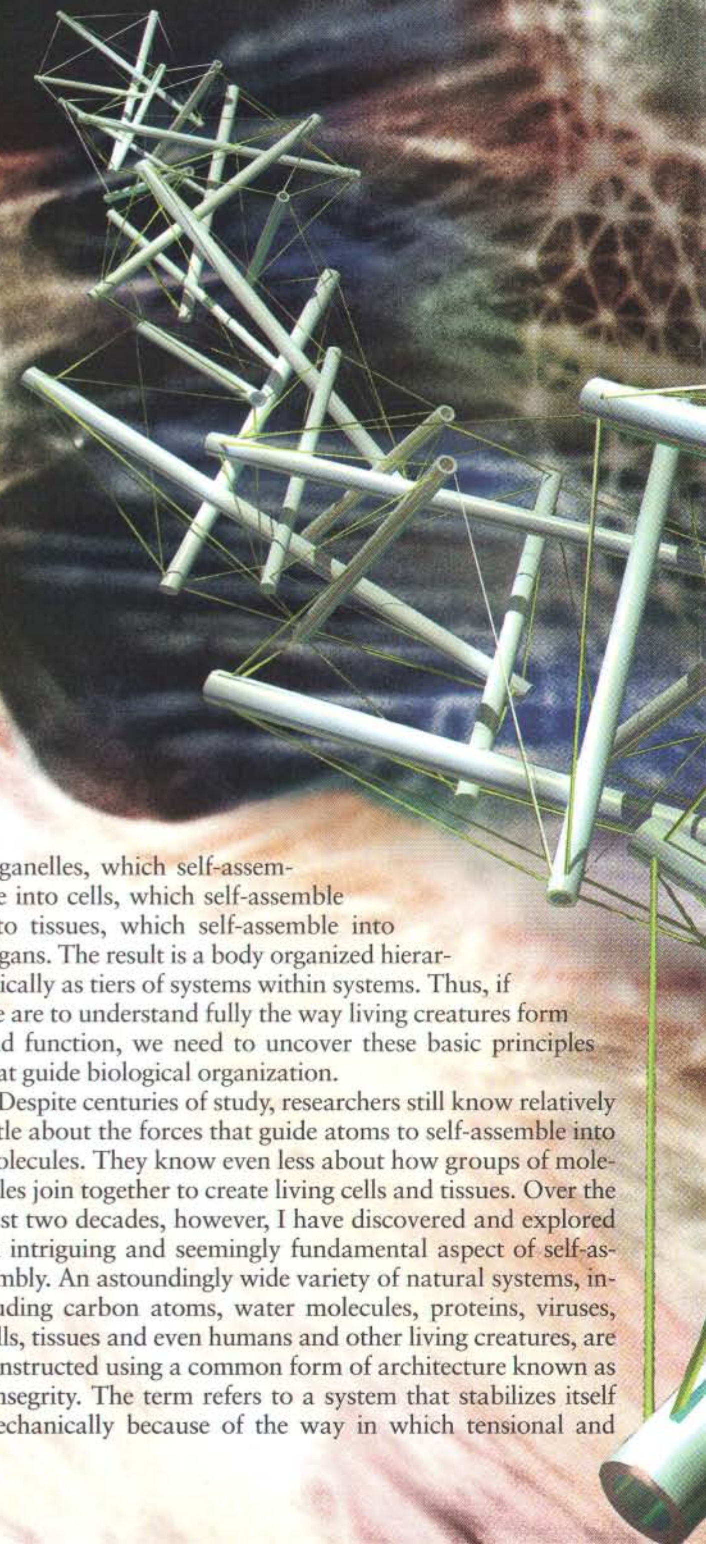
I'm all for any future that lessens the weight on my shoulders or makes it possible for the disabled to participate equally in society. But as I imagine using some of the wearables—walking down the street to power my personal-area network, the current TV news flowing onto the electronic paper notebook snapped into a pocket of my pieced-velvet trail vest sewn with conductive thread, my eyeglass display showing me where to turn, and my earpiece reading me my e-mail—I know I will long for the days when silence was as easy as leaving the cell phone home.

—*Wendy M. Grossman*
in Cambridge, Mass.

The Architecture of Life

A universal set of building rules seems to guide the design of organic structures—from simple carbon compounds to complex cells and tissues

by Donald E. Ingber



Life is the ultimate example of complexity at work. An organism, whether it is a bacterium or a baboon, develops through an incredibly complex series of interactions involving a vast number of different components. These components, or subsystems, are themselves made up of smaller molecular components, which independently exhibit their own dynamic behavior, such as the ability to catalyze chemical reactions. Yet when they are combined into some larger functioning unit—such as a cell or tissue—utterly new and unpredictable properties emerge, including the ability to move, to change shape and to grow.

Although researchers have recognized this intriguing fact for some time, most discount it in their quest to explain life's fundamentals. For the past several decades, biologists have attempted to advance our understanding of how the human body works by defining the properties of life's critical materials and molecules, such as DNA, the stuff of genes. Indeed, biologists are now striving to identify every gene in the complete set, known as the genome, that every human being carries. Because genes are the "blueprints" for the key molecules of life, such as proteins, this Holy Grail of molecular biology will lead in the near future to a catalogue of essentially all the molecules from which a human is created. Understanding what the parts of a complex machine are made of, however, does little to explain how the whole system works, regardless of whether the complex system is a combustion engine or a cell. In other words, identifying and describing the molecular puzzle pieces will do little if we do not understand the rules for their assembly.

That nature applies common assembly rules is implied by the recurrence—at scales from the molecular to the macroscopic—of certain patterns, such as spirals, pentagons and triangulated forms. These patterns appear in structures ranging from highly regular crystals to relatively irregular proteins and in organisms as diverse as viruses, plankton and humans. After all, both organic and inorganic matter are made of the same building blocks: atoms of carbon, hydrogen, oxygen, nitrogen and phosphorus. The only difference is how the atoms are arranged in three-dimensional space.

This phenomenon, in which components join together to form larger, stable structures having new properties that could not have been predicted from the characteristics of their individual parts, is known as self-assembly. It is observed at many scales in nature. In the human body, for example, large molecules self-assemble into cellular components known as organelles, which self-assemble into cells, which self-assemble into tissues, which self-assemble into organs. The result is a body organized hierarchically as tiers of systems within systems. Thus, if we are to understand fully the way living creatures form and function, we need to uncover these basic principles that guide biological organization.

Despite centuries of study, researchers still know relatively little about the forces that guide atoms to self-assemble into molecules. They know even less about how groups of molecules join together to create living cells and tissues. Over the past two decades, however, I have discovered and explored an intriguing and seemingly fundamental aspect of self-assembly. An astoundingly wide variety of natural systems, including carbon atoms, water molecules, proteins, viruses, cells, tissues and even humans and other living creatures, are constructed using a common form of architecture known as tensegrity. The term refers to a system that stabilizes itself mechanically because of the way in which tensional and

compressive forces are distributed and balanced within the structure.

This fundamental finding could one day have practical applications in many areas. For example, new understanding of tensegrity at the cellular level has allowed us to comprehend better how cellular shape and mechanical forces—such as pressure in blood vessels or compression in bone—influence the activities of genes. At the same time, deeper understanding of natural rules of self-assembly will allow us to make better use—in applications ranging from drug design to tissue engineering—of the rapidly accumulating data we have about molecules, cells and other biological components. An explanation of why tensegrity is so ubiquitous in nature may also provide new insight into the very forces that drive biological organization—and perhaps into evolution itself.

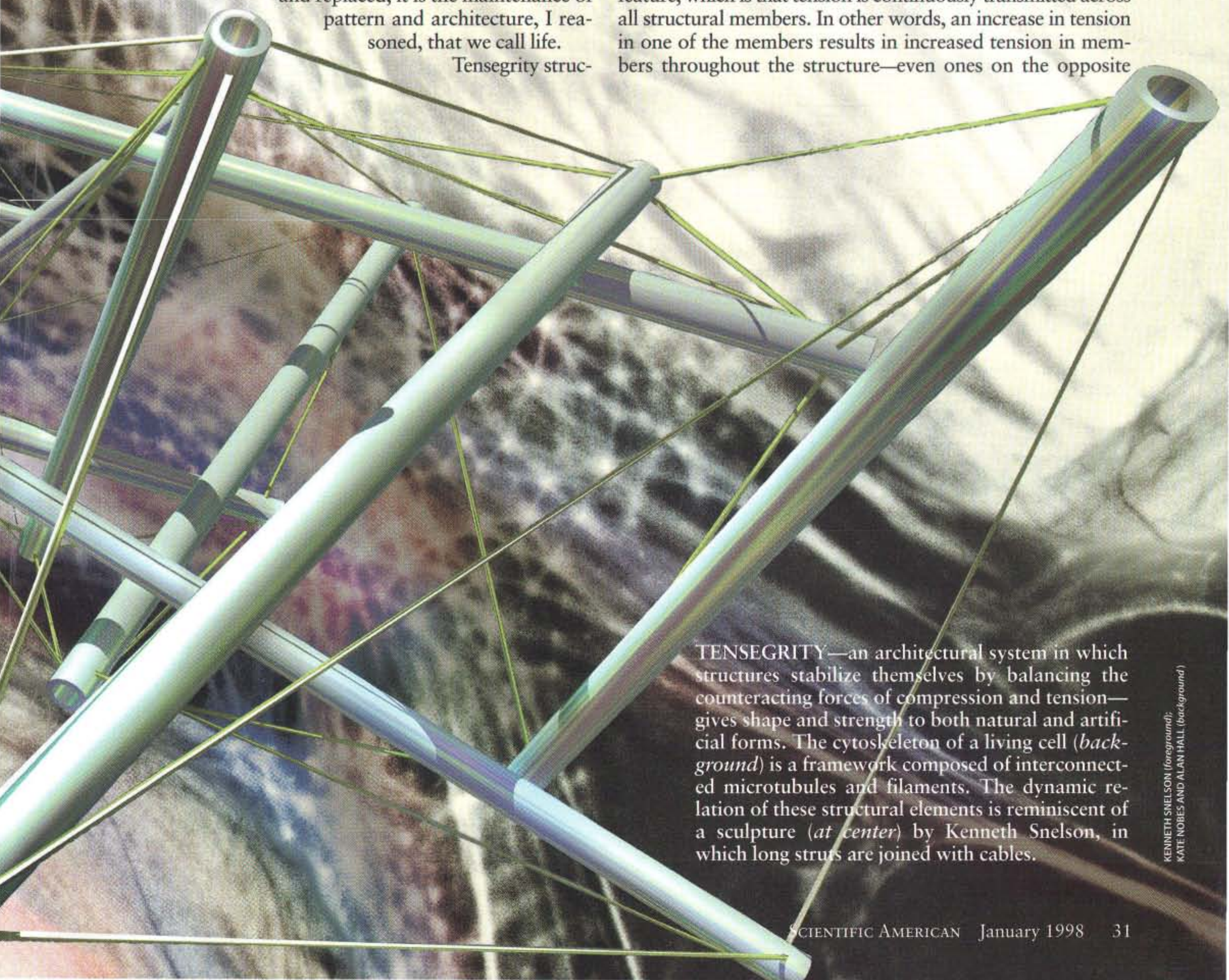
What Is Tensegrity?

My interest in tensegrity dates back to my undergraduate years in the mid-1970s at Yale University. There my studies of cell biology and also of sculpture led me to realize that the question of how living things form has less to do with chemical composition than with architecture. The molecules and cells that form our tissues are continually removed and replaced; it is the maintenance of pattern and architecture, I reasoned, that we call life.

Tensegrity structures are mechanically stable not because of the strength of individual members but because of the way the entire structure distributes and balances mechanical stresses. The structures fall into two categories. Structures in one category, which includes the geodesic domes of Buckminster Fuller, are basically frameworks made up of rigid struts, each of which can bear tension or compression. The struts that make up the framework are connected into triangles, pentagons or hexagons, and each strut is oriented so as to constrain each joint to a fixed position, thereby assuring the stability of the whole structure.

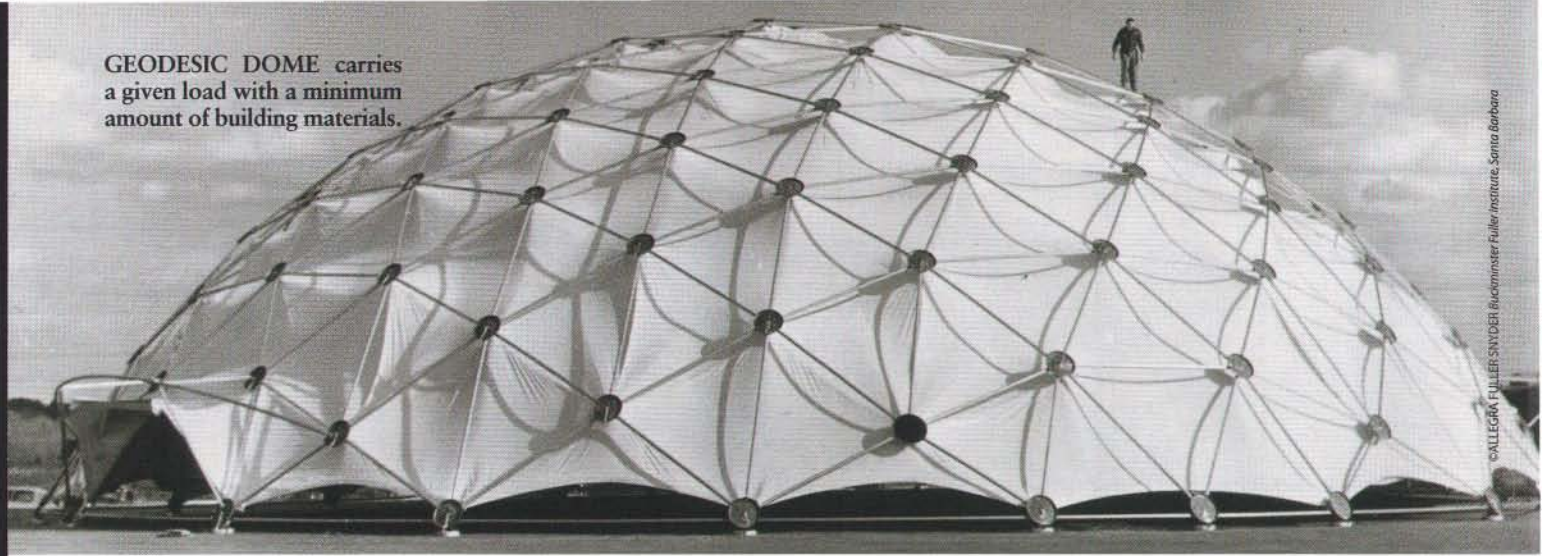
The other category of tensegrity structures encompasses those that stabilize themselves through a phenomenon known as prestress. This type of structure was first constructed by the sculptor Kenneth Snelson. In Snelson's elegant sculptures, structural members that can bear only tension are distinct from those that bear compression. Even before one of these structures is subjected to an external force, all the structural members are already in tension or compression—that is, they are prestressed. Within the structure, the compression-bearing rigid struts stretch, or tense, the flexible, tension-bearing members, while those tension-bearing members compress the rigid struts. These counteracting forces, which equilibrate throughout the structure, are what enable it to stabilize itself.

Tensegrity structures of both categories share one critical feature, which is that tension is continuously transmitted across all structural members. In other words, an increase in tension in one of the members results in increased tension in members throughout the structure—even ones on the opposite



TENSEGRITY—an architectural system in which structures stabilize themselves by balancing the counteracting forces of compression and tension—gives shape and strength to both natural and artificial forms. The cytoskeleton of a living cell (*background*) is a framework composed of interconnected microtubules and filaments. The dynamic relation of these structural elements is reminiscent of a sculpture (*at center*) by Kenneth Snelson, in which long struts are joined with cables.

KENNETH SNELSON (*foreground*); KATE NOBES AND ALAN HALL (*background*)



GEODESIC DOME carries a given load with a minimum amount of building materials.

side. This global increase in tension is balanced by an increase in compression within certain members spaced throughout the structure. In this way, the structure stabilizes itself through a mechanism that Fuller described as continuous tension and local compression. In contrast, most buildings derive their stability from continuous compression because of the force of gravity.

The tension-bearing members in these structures—whether Fuller's domes or Snelson's sculptures—map out the shortest paths between adjacent members (and are therefore, by definition, arranged geodesically). Tensional forces naturally transmit themselves over the shortest distance between two points, so the members of a tensegrity structure are precisely positioned to best withstand stress. For this reason, tensegrity structures offer a maximum amount of strength for a given amount of building material.

From Skeleton to Cytoskeleton

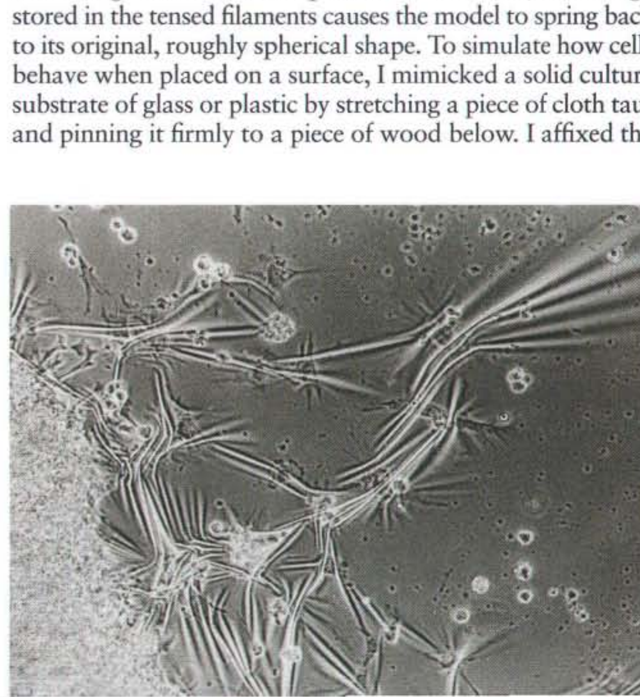
What does tensegrity have to do with the human body? The principles of tensegrity apply at essentially every detectable size scale in the body. At the macroscopic level, the 206 bones that constitute our skeleton are pulled up against the force of gravity and stabilized in a vertical form by the pull of tensile muscles, tendons and ligaments (similar to the cables in Snelson's sculptures). In other words, in the complex tensegrity structure inside every one of us, bones are the compression struts, and muscles, tendons and ligaments are the tension-bearing members. At the other end of the scale, proteins and other key molecules in the body also stabilize themselves through the principles of tensegrity. My own interest lies in between these two extremes, at the cellular level.

As a graduate student working with James D. Jamieson at Yale, I focused on how the components of biological systems—especially of cells—interacted mechanically. At this time, in the late 1970s, biologists generally viewed the cell as a viscous fluid or gel surrounded by a membrane, much like a balloon filled with molasses. Cells were known to contain an internal framework, or cytoskeleton, composed of three different types of molecular protein polymers, known as microfilaments, intermediate filaments and microtubules. But their role in controlling cell shape was poorly understood.

Another mystery in those days concerned the way isolated cells behave when placed on different surfaces. It had been long known that cells spread out and flatten when they attach to a rigid glass or plastic culture dish. In 1980, however, Albert K. Harris of the University of North Carolina at Chapel Hill showed that when affixed to a flexible rubber substrate, cells contract and become more spherical. This contraction bunches up, or puckers, the underlying rubber.

It occurred to me that a view of the cell as a tensegrity structure could easily explain such behavior. I modeled a cell as such a structure; it consisted of six wood dowels and some elastic string. I arranged the dowels—which bore the compressive stress—in three pairs. Each pair was perpendicular to the other two, and none of the wood struts actually touched one another. A tension-bearing elastic string connected to the ends of all the dowels, pulling them into a stable, three-dimensional form. I also placed a smaller, spherical tensegrity model, representing the nucleus, within the larger one that represented the rest of the cell. Then, to mimic cytoskeletal connections between the nucleus and the rest of the cell, I stretched elastic strings from the surface of the large tensegrity structure to the smaller one inside [*see illustration at top right on opposite page*].

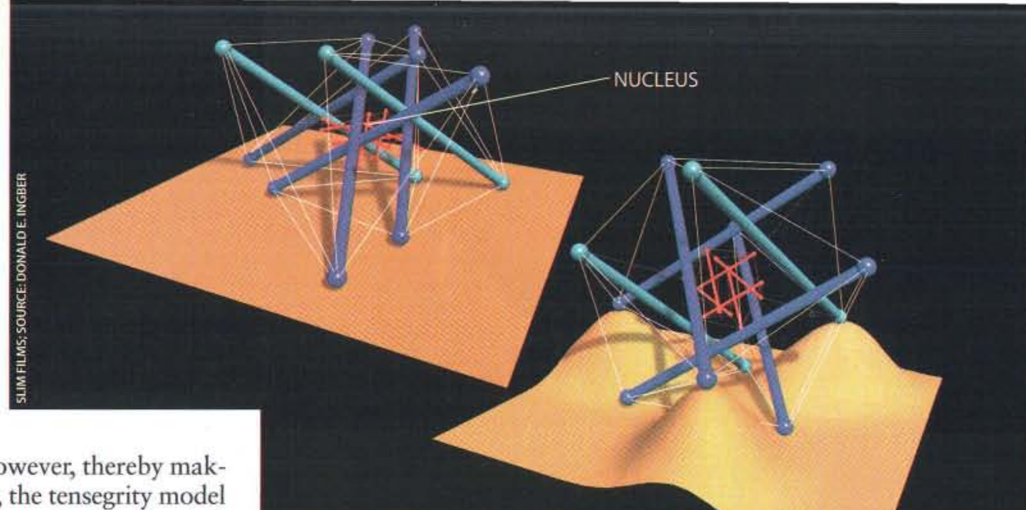
To understand how my experiment worked, it is necessary to know that pushing down on a tensegrity model of the kind I built forces it into what appears to be a flattened pile of sticks and string. As soon as the pressure is removed, the energy stored in the tensed filaments causes the model to spring back to its original, roughly spherical shape. To simulate how cells behave when placed on a surface, I mimicked a solid culture substrate of glass or plastic by stretching a piece of cloth taut and pinning it firmly to a piece of wood below. I affixed the



LIVING CELLS crinkle a thin rubber substrate because they exert tractional forces where they adhere.

tensegrity model to the substrate by flattening it and sewing the ends of some of the dowels to the cloth. These attachments were analogous to the cell-surface molecules, now known as integrins or adhesion receptors, that physically connect a cell to its anchoring substrate.

With the dowel ends sewed to the tightly pinned cloth, the model remained flat, just as a real cell does on a hard substrate. When I lifted the pins to free the cloth from the wood, however, thereby making the cell's anchoring surface flexible, the tensegrity model popped up into its more spherical form, puckering the cloth underneath. Furthermore, I noticed that when I stretched the model flat by connecting it to the cloth substrate, the cell and nucleus inside it extended in a coordinated manner. The nucleus model also moved toward the bottom of the simulated cell. Soon thereafter, I showed experimentally that living cells and nuclei spread and polarize in a similar manner when they adhere to a substrate. Thus, with my highly simplified construction, I showed that tensegrity structures mimic the known behavior of living cells.

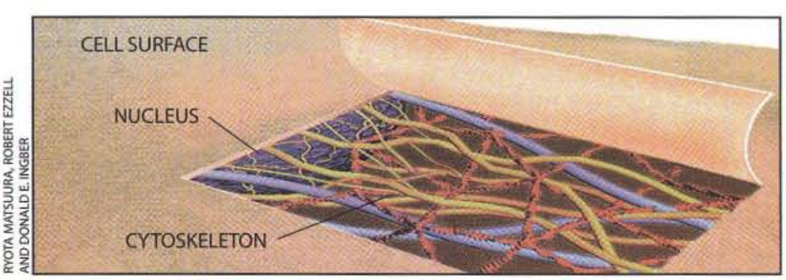


TENSEGRITY MODEL of a cell was built with dowels and elastic cords. Like a living cell, it flattens itself and its nucleus when it attaches to a rigid surface (*left*) and retracts into a more spherical shape on a flexible substrate, puckering that surface (*right*).

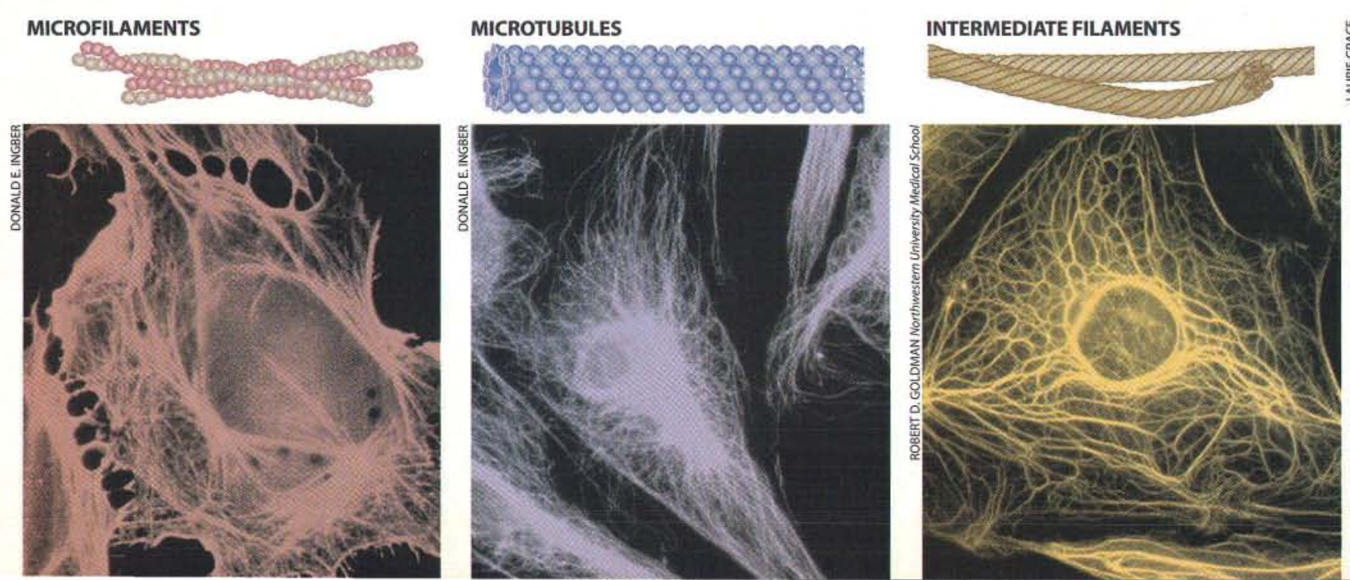
Hard-Wiring in Cells

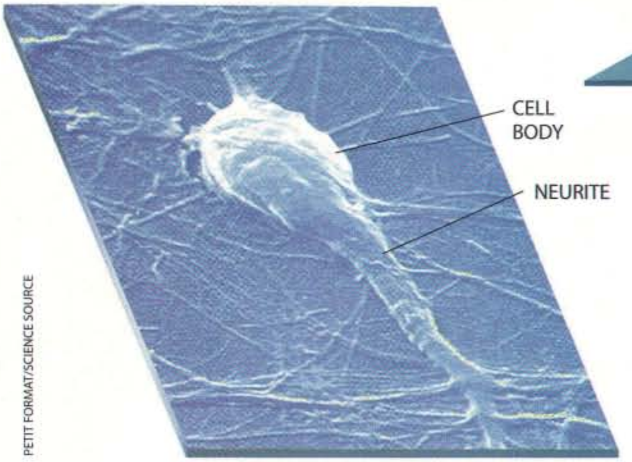
In the years since my modeling experiment, biologists have learned a great deal about the mechanical aspects of cells, and their findings seem to confirm that cells do indeed get their shape from tensegrity. Further, just as the models predict, most cells derive their structure not only from the cytoskeleton's three major types of filaments but also from the extracellular matrix—the anchoring scaffolding to which cells are naturally secured in the body.

Inside the cell, a gossamer network of contractile microfilaments—a key element of the cytoskeleton—extends throughout the cell, exerting tension. In other words, it pulls the cell's membrane and all its internal constituents toward the nucleus at the core. Opposing this inward pull are two main types of compressive elements, one of which is outside the cell and the other inside. The component outside the cell is the extracellular matrix; the compressive "girders" inside the cell can be either microtubules or large bundles of cross-linked microfilaments within the cytoskeleton. The third component of the cytoskeleton, the intermediate filaments, are the great integrators, connecting microtubules and contractile microfilaments to one another as well as to the surface membrane and the cell's nucleus. In addition, they act as guy wires, stiff-

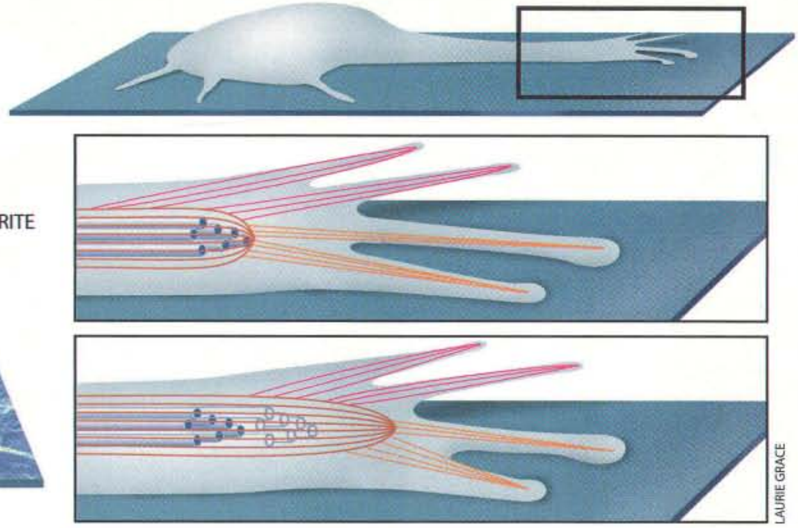


CYTOSKELETON of a cell consists of microfilaments (*bottom left*), microtubules (*bottom center*) and intermediate filaments (*bottom right*), all of which are nanometers wide. The rounded shape near the center in each of these photographs is the cell nucleus. The three components interconnect to create the cytoskeletal lattice, which stretches from the cell surface to the nucleus (*top left*). The molecular structure of each component is shown above the corresponding photograph and is color coded to the top left illustration.





PETIT FORMAT/SCIENCE SOURCE



LAURIE GRACE

NERVE CELL has long extensions, called neurites, that connect electrically with neighboring nerve cells (*above left* and *top right*). Neurites extend from the cell (*views at right*), for example, during the repair of an injury, by elongating internal molecular fibers known as microtubules (*purple*). Contractile microfilaments (*red*) surround the microtubules, compressing them and restricting their growth. The same microfilaments, however, are connected to other ones (*orange*) that extend forward to the points where the cell anchors to its underlying substrate (*center*). When the microfilaments pull themselves forward against these adhesions, they enable the microtubules to elongate, and the neurite extends (*bottom*).

ening the central nucleus and securing it in place. Although the cytoskeleton is surrounded by membranes and penetrated by viscous fluid, it is this hard-wired network of molecular struts and cables that stabilizes cell shape.

If the cell and nucleus are physically connected by tensile filaments and not solely by a fluid cytoplasm, then pulling on receptors at the cell surface should produce immediate structural changes deep inside the cell. Recently Andrew Maniotis, who was in my group at Children's Hospital of Harvard Medical School, demonstrated this directly. By binding micropipettes to adhesion receptors on the surface of living cells and pulling outward, Maniotis caused cytoskeletal filaments and structures in the nucleus to realign immediately in the direction of pull. Thus, as my early experiments suggested, cells and nuclei do not behave like viscous water balloons.

How Mechanics Controls Biochemistry

Tensegrity can be invoked to explain more than the stabilization of cellular and nuclear form. For example, Steven R. Heidemann, working with Harish Joshi and Robert E. Buxbaum of Michigan State University in the mid-1980s, found that tensegrity can explain how nerve cells extend long, thin projections called neurites, which are filled with microtubules and transmit electrical signals in the nervous system. This growth is required for repair of nerve damage.

Heidemann's group found that microtubules are compressed at their ends by the pull of surrounding contractile microfilaments inside the neurites. More important, the researchers discovered that microtubule assembly (elongation)—and, hence, neurite extension—is promoted by shifting compressive loads off the microtubule and onto the cell's attachments to its extracellular matrix. In other words, the existence of a tensegrity force balance provides a means to integrate mechanics and biochemistry at the molecular level.

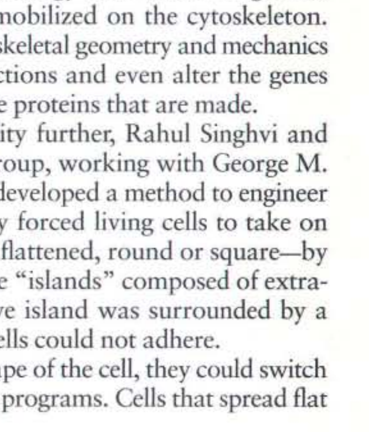
Very recently, Andrew Matus of the Friedrich Miescher Institute in Basel added a vivid footnote to this story. By making cells that produce fluorescent microtubules, Matus actually viewed those microtubules buckling under compression.

The tensegrity model suggests that the structure of the cell's cytoskeleton can be changed by altering the balance of physical forces transmitted across the cell surface. This finding is important because many of the enzymes and other substances that control protein synthesis, energy conversion and growth in the cell are physically immobilized on the cytoskeleton. For this reason, changing cytoskeletal geometry and mechanics could affect biochemical reactions and even alter the genes that are activated and thus the proteins that are made.

To investigate this possibility further, Rahul Singhvi and Christopher S. Chen in my group, working with George M. Whitesides, also at Harvard, developed a method to engineer cell shape and function. They forced living cells to take on different shapes—spherical or flattened, round or square—by placing them on tiny, adhesive "islands" composed of extracellular matrix. Each adhesive island was surrounded by a Teflon-like surface to which cells could not adhere.

By simply modifying the shape of the cell, they could switch cells between different genetic programs. Cells that spread flat became more likely to divide, whereas round cells that were prevented from spreading activated a death program known as apoptosis. When cells were neither too extended nor too retracted, they neither divided nor died. Instead they differentiated themselves in a tissue-specific manner: capillary cells formed hollow capillary tubes; liver cells secreted proteins that the liver normally supplies to the blood; and so on.

Thus, mechanical restructuring of the cell and cytoskeleton apparently tells the cell what to do. Very flat cells, with their cytoskeletons



STEFANIE KAECH, BEAT LUDIN AND ANDREW MATUS

GROWING MICROTUBULE buckles under compression in these time-lapse video images. The buckling occurs when the microtubule elongates and pushes against other components of the cell's skeleton.

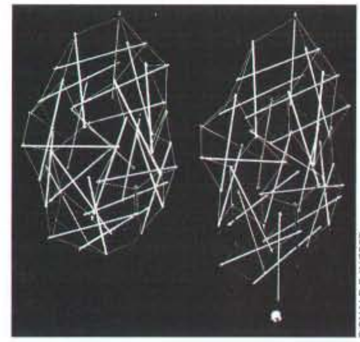
stretched, sense that more cells are needed to cover the surrounding substrate—as in wound repair—and that cell division is needed. Rounding indicates that too many cells are competing for space on the matrix and that cells are proliferating too much; some must die to prevent tumor formation. In between these two extremes, normal tissue function is established and maintained. Understanding how this switching occurs could lead to new approaches to cancer therapy and tissue repair and perhaps even to the creation of artificial-tissue replacements.

Making Cells Do the Twist

The next level up in the hierarchy of self-assembly is the formation of tissues, which are created from the joining of cells to one another and to their extracellular matrix. One emergent property of tissues is how they behave mechanically. Many different types of tissue, including muscle, cartilage, blood vessels and skin, exhibit a response known as linear stiffening. If you pull on your skin, for example, you will feel the resistance increase as you tug harder. An increasing external force is met with increasing resistance. Recent studies show that even isolated molecules, such as DNA, exhibit linear stiffening, yet until we examined this phenomenon in the context of tensegrity, there was no mechanical or mathematical explanation for this behavior.

In 1993 my co-worker Ning Wang, working with James P. Butler of the Harvard School of Public Health, developed a device that allowed us to twist individual molecules on the surface membrane of living cells while simultaneously measuring the cellular response. We found that when we increased the stress applied to integrins (molecules that go through the cell's membrane and link the extracellular matrix to the internal cytoskeleton), the cells responded by becoming stiffer and stiffer—just as whole tissues do. Furthermore, living cells could be made stiff or flexible by varying the prestress in the cytoskeleton by changing, for example, the tension in contractile microfilaments.

Although the exact details of the interaction are not all known, we showed, using a stick-and-string tensegrity model, that the gist of the response can be discerned from the way in which tensegrity structures respond to stress. Essentially, all the interconnected structural elements of a tensegrity model rearrange themselves in response to a local stress. Linear stiffening results because as the applied stress increases, more of the members come to lie in the direction of the applied stress.



LINEAR STIFFENING occurs in a tensegrity structure because structural members reorient themselves to lie more in the direction of applied stress (downward in the right-hand view).

DONALD E. INGBER

Working with Dimitrije Stamenovic of Boston University, we developed a mathematical model based on these principles. It predicts, for the first time, the linear-stiffening response of tissues, living cells and even molecules. We hope to use this model to help design advanced materials that have the linear-stiffening property and that may be useful in such applications as protective clothing and artificial body parts. The same mathematical approach may also be incorporated within computer programs as a shortcut to accelerate molecular modeling and drug design.

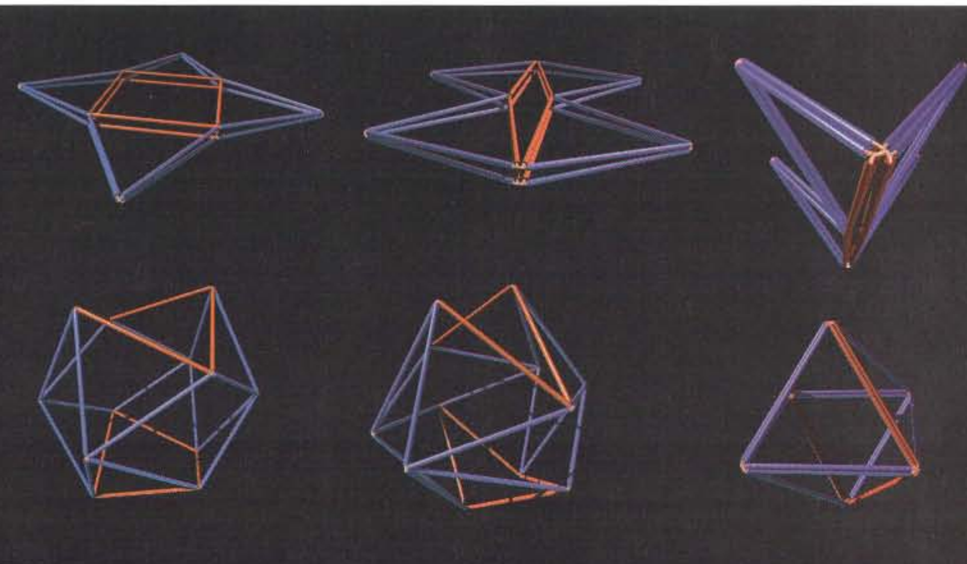
In Wang's magnetic-twisting studies and in Maniotis's micropipette-pulling experiments, we found that applying stress to cell-surface receptors involved with metabolism—rather than adhesion—did not effectively convey force to the inside of the cell. Thus, these studies confirmed that mechanical forces are transmitted over specific molecular paths in living cells, a finding that provided new insight into how cells sense mechanical stimuli that regulate tissue development. This insight, in turn, may help us better understand a wide variety of phenomena, from the growth of muscle in response to tension to the growth of plant roots in response to gravity.

Molecular Geodesic Domes

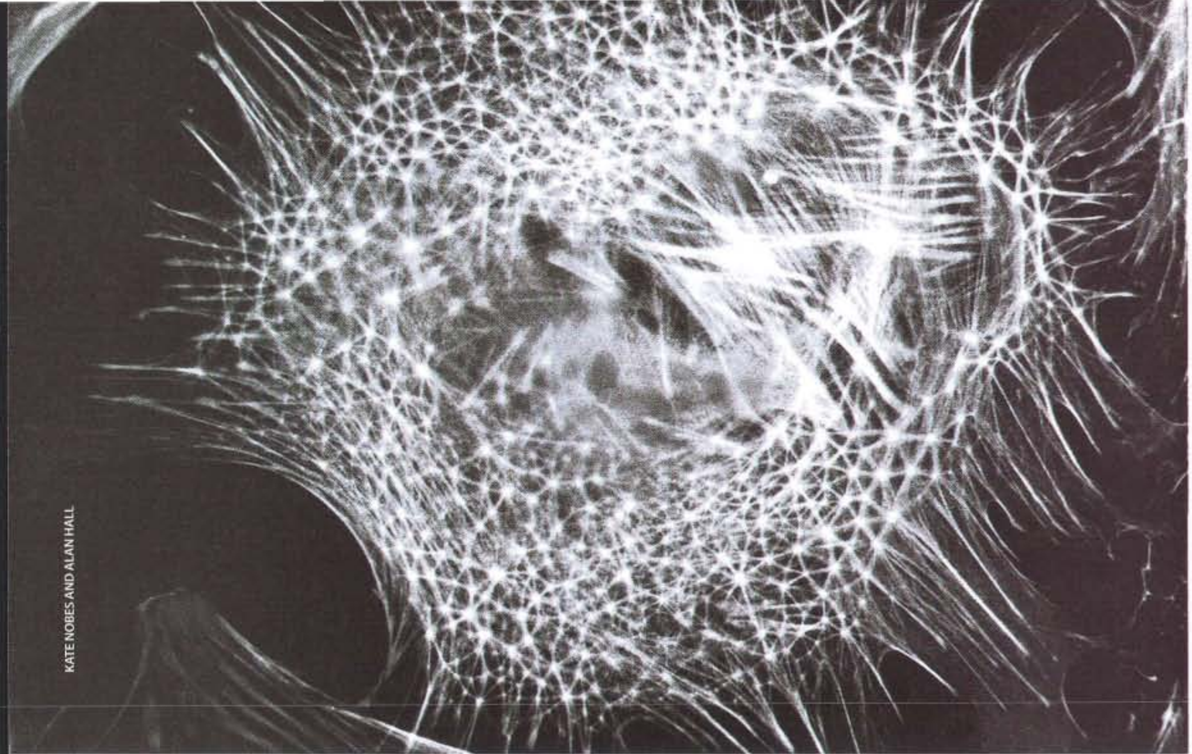
Although the tensegrity models predicted many cell behaviors, one disparity needed explaining. Many cells can spread and flatten without microtubules—the most important compression struts in the model. If living cells can change from spherical to flat without these struts, how can tensegrity apply? Again using an uncomplicated modeling approach, I found that, incredibly, the microfilament network itself is a tensegrity structure.

In the cytoskeleton of a living cell, contractile microfilaments form a lattice that reorganizes locally into different forms, such as large bundles or networks of triangles. To explore the

SODA-STRAW MODEL (*below*) with flexible joints shows how contracting microfilament networks can rearrange into linear bundles (*top right*) or triangulated geodesic forms, such as the octahedron (*bottom right*).



SLIM FILMS; SOURCE: DONALD E. INGBER



KATE NOBES AND ALAN HALL

FRANCIS LEROY *Biocosmos/ SPL Photo Researchers, Inc.*

KEN EWARD *BioGrafx/Science Source/Photo Researchers, Inc.*

GEODESIC FORMS appear in many different natural structures, including part of the cytoskeleton of a mammalian cell (*above left*), an adenovirus (*top middle*) and (*clockwise from bottom right*) a pollen grain, a buckyball surrounding a potassium ion, a protein enzyme complex and a multicellular organism known as a volvox.

mechanism behind this reorganization, I modeled the microfilament lattice as a polyhedral framework of soda straws that contained six triangles and four squares [*see bottom illustration on preceding page*]. The straws were held together by a single elastic string that I threaded through all the straws and tied to itself. I assumed that each soda straw in the model represented a single contractile microfilament that could generate mechanical tension by shortening itself. It is known that contractile microfilaments get stiffer when they shorten. Thus, the internal elastic thread in the model would then mimic the continuous tension in the whole structure that results from the shortening of all these stiffened filaments.

I assumed that this soda-straw model represented one modular cytoskeletal unit that interconnected in all directions with other similar modules in a round, unattached (suspended) cell. The question I was trying to answer was, What would happen to this framework if the cell it supported were to attach to a rigid surface?

Cells attach by binding to surface-bound molecules in the extracellular matrix. But cells are not evenly "glued" to the matrix; rather they are "spot welded" in localized sites known as focal adhesions. Contractile microfilaments respond to anchorage by shortening and increasing isometric tension within the lattice. The soda-straw models suggested that the increasing tension produced by attachment would cause the individual contractile microfilaments that formed the squares in the model to self-assemble into linear bundles stretching between these focal-adhesion sites where integrin receptors anchor the cell to the matrix. In fact, when living cells spread on a surface, individual contractile microfilaments align in a nearly identical manner to form bundles called stress fibers.

In contrast, at the top of the cell, there is no adhesive substrate to resist the pull of the shortening microfilaments. In these regions the contraction of each microfilament can be resisted only by the pull and stiffness of its neighboring filaments. Fuller showed many years ago that inward pulling and twisting causes this type of polyhedral structure to undergo what he called a "jitterbug" transformation: the highly flexible framework of squares and triangles converts into fully triangulated octahedral or tetrahedral forms—or, in other words, into fully triangulated tensegrity structures.

When I interconnected many similar soda-straw models, I found that the individual modules progressively contracted, resulting in the formation of a geodesic framework composed of alternating octahedral and tetrahedral forms, closely packed. In a cell, contraction of surrounding microfilament networks that interconnect with the cell base would bend this framework down over the spherical nucleus, thereby transforming it into a highly triangulated dome—specifically, a geodesic dome.

Elias Lazarides, then at Cold Spring Harbor Laboratory in New York, and Mary Osborn and Klaus Weber of the Max Planck Institute in Göttingen, Germany, observed these very transformations in the region of the cytoplasm above the nucleus in spreading cells. Significantly, the existence of a geodesic dome within the cytoskeleton at the molecular level demonstrates conclusively that cells can and do use the architecture of tensegrity to shape their cytoskeleton.

A Universal Pattern

The geodesic structure found within the cytoskeleton is a classic example of a pattern that is found everywhere in nature, at many different size scales. Spherical groups of carbon atoms called buckminsterfullerenes or buckyballs, along with viruses, enzymes, organelles, cells and even small organisms,

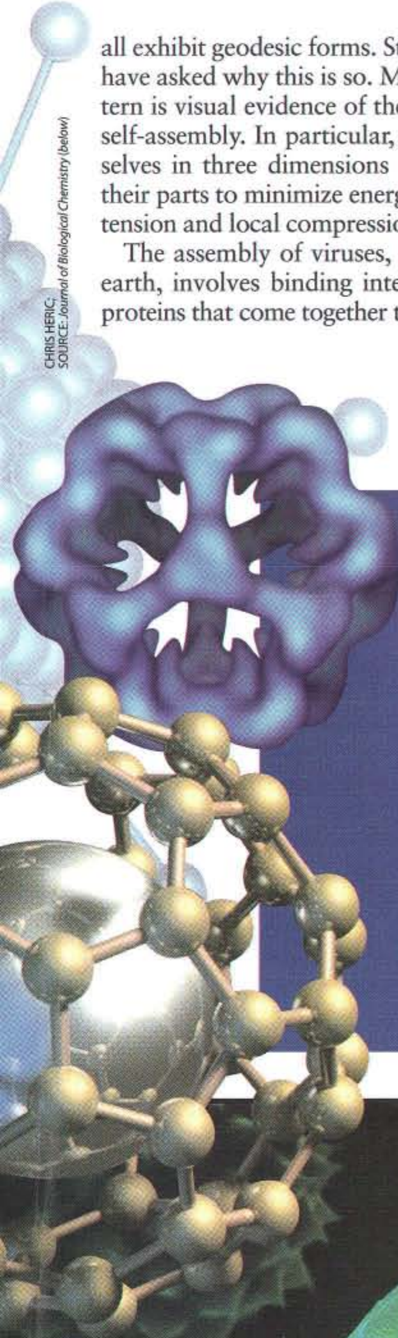
all exhibit geodesic forms. Strangely, few researchers seem to have asked why this is so. My view is that this recurrent pattern is visual evidence of the existence of common rules for self-assembly. In particular, all these entities stabilize themselves in three dimensions in a similar way: by arranging their parts to minimize energy and mass through continuous tension and local compression—that is, through tensegrity.

The assembly of viruses, the smallest form of life on the earth, involves binding interactions between many similar proteins that come together to form a geodesic viral coat that encloses the genetic material. During virus formation, linear extensions of the proteins overlap with similar tails that extend from neighboring proteins to form a triangulated geodesic framework on the nanometer scale. Each joint in this framework self-stabilizes as a result of a balance between the pull of intermolecular attractive forces (hydrogen bonds) and the ability of the individual protein tails to resist compression and buckling.

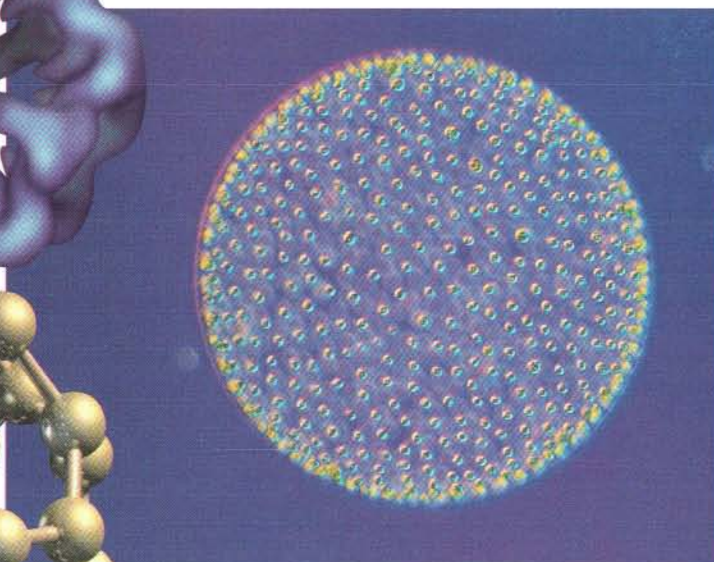
The same basic scheme is apparent in buckyballs, except that the building blocks are atoms instead of proteins. In buckyballs, 60 carbon atoms form a geodesic sphere covered by 20 hexagons interspersed with 12 pentagons: the pattern on a soccer ball. In effect, the 90 carbon-carbon bonds in a buckyball are the struts in a tensegrity sphere.

It is more difficult, however, to see that the same building rules also apply to irregular structures, including many biological molecules, that do not exhibit geodesic forms. Proteins, on which cells depend for structure, catalysis and many other functions, are long strings of amino acids. Small regions of the protein's amino acid backbone fold into helical forms that stabilize themselves through a balance between the attractive force of hydrogen bonds (pulling together different regions of the molecule) and the ability of the protein coil to resist shortening, or compression. In other words, these helical regions stabilize themselves through tensegrity—as does any helical molecule, such as DNA.

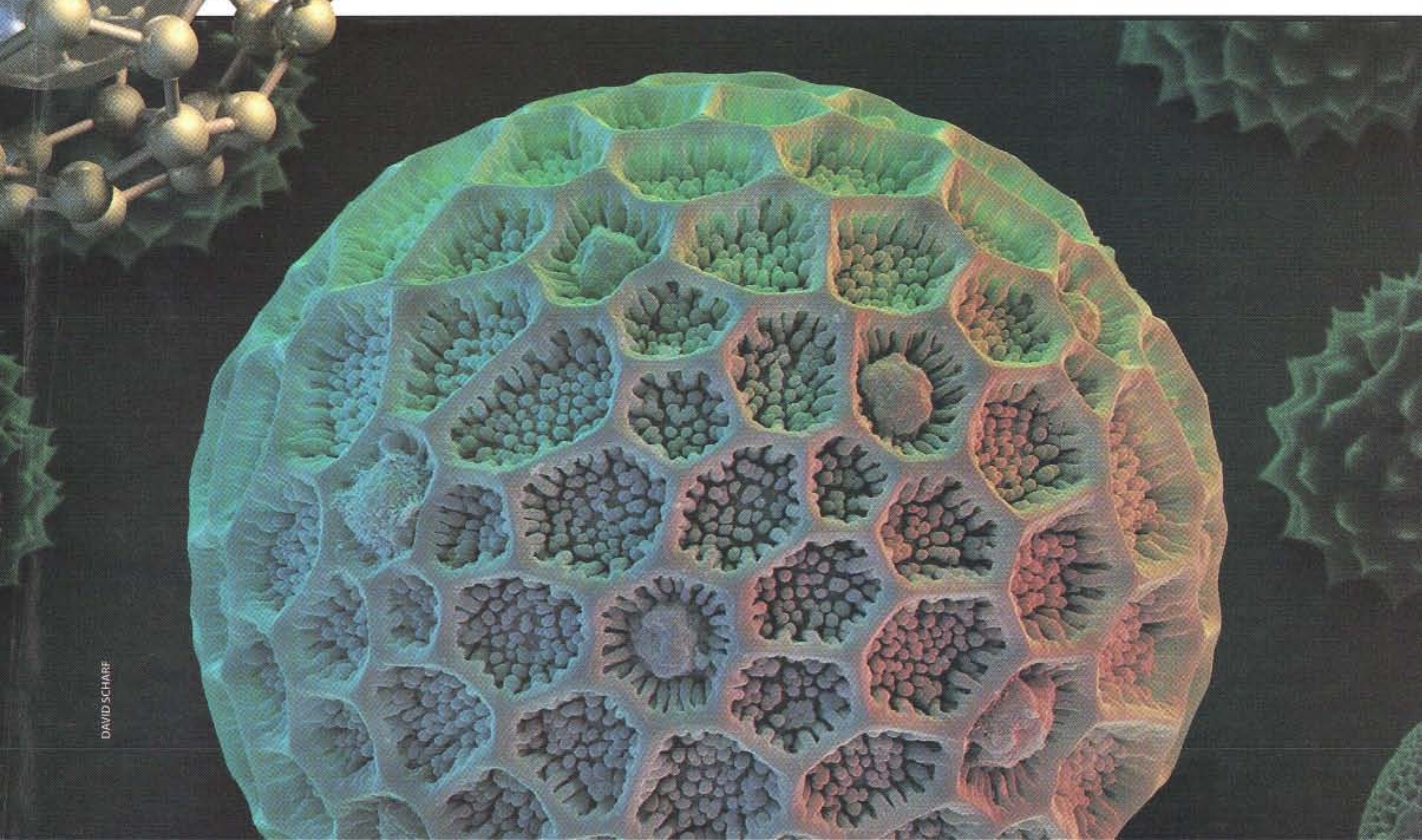
Protein organization also involves hierarchical assembly. The small regions of a protein that are helically stiffened are separated from one another by parts of the same amino acid



CHRIS HERIC; SOURCE: *Journal of Biological Chemistry* (below)



M. ABBEY *Photo Researchers, Inc.*



DAVID SCHARF


JIM AND JULIE BRUTON Photo Researchers, Inc.

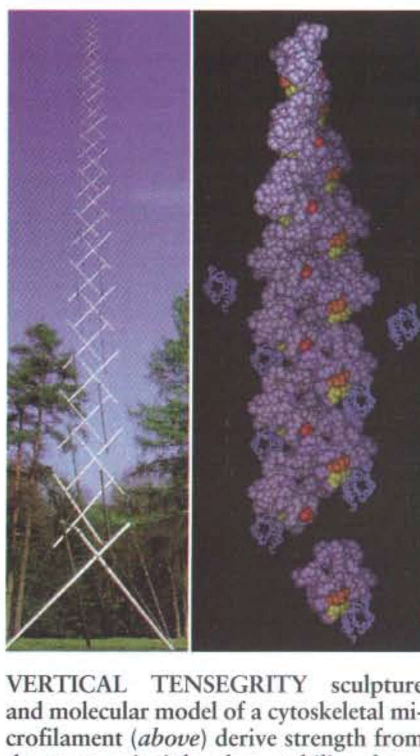
PRESTRESSED TENSEGRITY CANTILEVERS include the muscle-and-bone neck of a giraffe and a cable-and-beam sculpture by Kenneth Snelson.

backbone that act as if they were flexible hinges. These strutlike regions fold back on themselves (because of tensile hydrogen-bonding forces) in order to stabilize the entire molecule. The stiffened helices may be extremely compressed locally, even though forces are equilibrated across the whole prestressed molecule.

Because a local force can change the shape of an entire tensegrity structure, the binding of a molecule to a protein can cause the different, stiffened helical regions to rearrange their relative positions throughout the length of the protein. For example, when a signal-bearing molecule binds to a receptor that goes through the membrane and into a cell, the attachment can cause conformational changes at the opposite end of the receptor. These conformational changes, in turn, alter the shape of adjacent proteins and trigger a cascade of molecular restructuring inside that cell. Indeed, this is how cells sense and respond to changes in their environment.

Thus, from the molecules to the bones and muscles and tendons of the human body, tensegrity is clearly nature's preferred building system. Only tensegrity, for example, can explain how every time that you move your arm, your skin stretches, your extracellular matrix extends, your cells distort, and the interconnected molecules that form the internal framework of the cell feel the pull—all without any breakage or discontinuity.

Remarkably, tensegrity may even explain how all these phenomena are so perfectly coordinated in a living creature. At the Johns Hopkins School of Medicine, Donald S. Coffey and Kenneth J. Pienta found that tensegrity structures function as coupled harmonic oscillators. DNA, nuclei, cytoskeletal filaments, membrane ion channels and entire living cells and tissues exhibit characteristic resonant frequencies of vibration. Very simply, transmission of tension through a tensegrity array provides a means to distribute forces to all interconnected elements and, at the same time, to couple, or "tune," the whole system mechanically as one.


KENNETH SNELSON (left); CLARENCE E. SCHUTT (right)

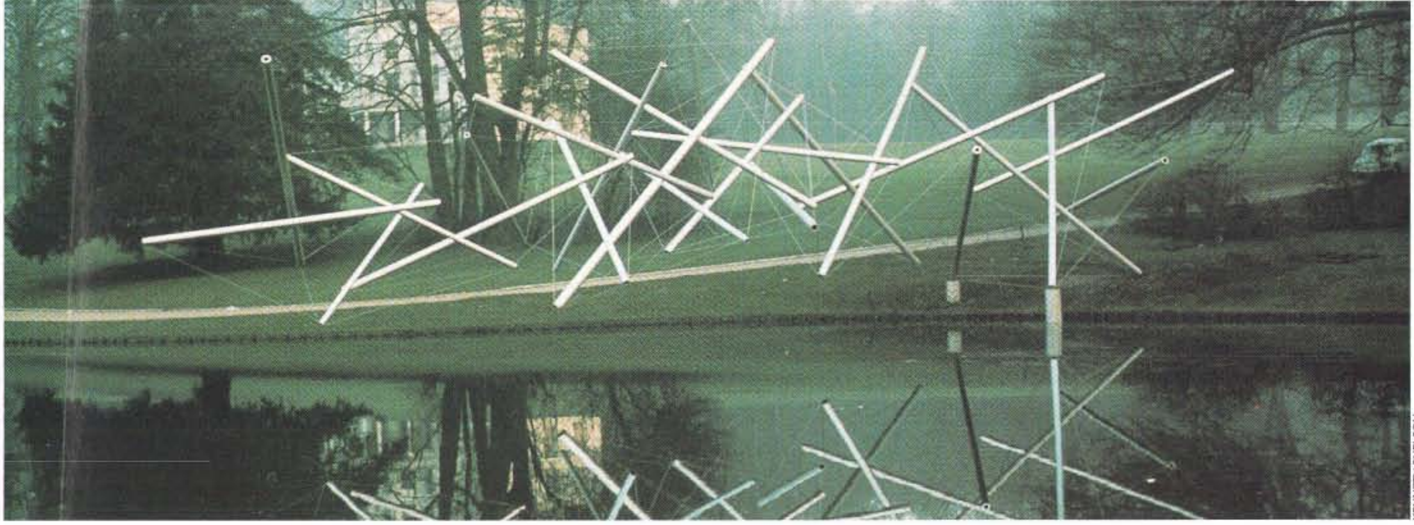
VERTICAL TENSEGRITY sculpture and molecular model of a cytoskeletal microfilament (*above*) derive strength from the same principle: they stabilize themselves through a balance of compression and tension. In the surface tissue of a fly's eye (*background at right*), cells are arranged geodesically for the same purpose—to provide stability through continuous tension and local compression.

Implications for Evolution and Beyond

Although changes in DNA generate biological diversity, genes are a product of evolution, not its driving force. In fact, geodesic forms similar to those found in viruses, enzymes and cells existed in the inorganic world of crystals and minerals long before DNA ever came into existence. Even water molecules are structured geodesically.

The relevant question is, How did organic molecules and cells evolve from inorganic components? After all, in terms of how emergent properties arise, self-assembly of molecules into organelles or cells into tissues is not very different from the self-assembly of atoms into compounds. For example, sodium, an explosive metal, and chlorine, a poisonous gas, combine to form sodium chloride, whose emergent property is that it can be used as table salt. The important principle here is the manner in which a structure shapes itself and holds its subcomponents together in three-dimensional space; this characteristic is what defines the way the structure as a whole will behave.

More broadly, all matter is subject to the same spatial constraints, regardless of scale or position. Thus, given these constraints, tensegrity is the most economical and efficient way to build—at the molecular scale, at the macroscopic scale and at all scales in between. It is possible that fully triangulated tensegrity structures may have been selected through evolution because of their structural efficiency—their high mechanical strength using a minimum of materials. The flexibility exhibited by prestressed tensegrity structures would be advanta-



KENNETH SNELSON

geous because it allows structures to take on different shapes. For example, if a molecule or cell were able to transform into a shape that was more stable at a certain temperature or pressure, or more efficient metabolically, then its lifetime would have been extended. It would have been more likely to interact with other, similar entities and then to self-assemble once again.

Researchers now think biological evolution began in layers of clay, rather than in the primordial sea. Interestingly, clay is itself a porous network of atoms arranged geodesically within octahedral and tetrahedral forms. But because these octahedra and tetrahedra are not closely packed, they retain the ability to move and slide relative to one another. This flexibility apparently allows clay to catalyze many chemical reactions, including ones that may have produced the first molecular building blocks of organic life.

Over time, different molecular collectives self-assembled to form the first structures with specialized functions—the forerunners of present-day organelles—which then combined with one another to create the first simple cells. These cells then produced proteins that self-assembled to form extracellular matrix–anchoring scaffolds that, in turn, promoted self-assembly of multicellular tissues. Organs developed from the self-assembly of tissues, and complex organisms arose through combination and progressive remodeling of different organs. Indeed, the development of an embryo from a sperm and an egg recapitulates all these stages of self-assembly.

The emergence of DNA and genes gave rise to a new mechanism for generating structural diversity that accelerated evolution. Yet throughout all this time the rules guiding the process of hierarchical self-assembly remained essentially unchanged. So it is no surprise that the basic arrangement of bones and muscles is remarkably similar in *Tyrannosaurus rex* and *Homo sapiens;* that animals, insects and plants all rely on prestress for the mechanical stability of their bodies; and that geodesic forms, such as hexagons, pentagons and spirals, predominate in natural systems.

Finally, more philosophical questions arise: Are these building principles universal? Do they apply to structures that are molded by very large scale forces as well as small-scale ones? We do not know. Snelson, however, has proposed an intriguing model of the atom based on tensegrity that takes off where the French physicist Louis de Broglie left off in 1923. Fuller himself went so far as to imagine the solar system as a structure composed of multiple nondeformable rings of planetary motion held together by continuous gravitational tension. Then, too, the fact that our expanding (tensing) universe contains huge filaments of gravitationally linked galaxies and isolated black holes that experience immense compressive forces locally can only lead us to wonder. Perhaps there is a single underlying theme to nature after all. As suggested by early 20th-century Scottish zoologist D'Arcy W. Thompson, who quoted Galileo, who, in turn, cited Plato: the Book of Nature may indeed be written in the characters of geometry. SA

The Author

DONALD E. INGBER, who holds B.A., M.A., M.Phil., M.D. and Ph.D. degrees from Yale University, is an associate professor of pathology at Harvard Medical School and a research associate in the departments of surgery and pathology at Children's Hospital in Boston. He is also a member of the Center for Bioengineering at the Massachusetts Institute of Technology. In addition to his work on cell structure, Ingber has contributed to the study of tumor angiogenesis, including the discovery of an anticancer drug now in clinical trials. He is the founder of Molecular Geodesics, Inc., a Cambridge, Mass., company that creates advanced materials with biologically inspired properties.

JENNIFER R. McCABE

Further Reading

ON GROWTH AND FORM. Revised edition. D'Arcy W. Thompson. Cambridge University Press, 1942 (reprinted 1992).

MOVEMENT AND SELF-CONTROL IN PROTEIN ASSEMBLIES. Donald L. D. Caspar in *Biophysical Journal,* Vol. 32, No. 1, pages 103–138; October 1980.

CLAY MINERALS AND THE ORIGIN OF LIFE. Edited by A. Graham Cairns-Smith and Hyman Hartman. Cambridge University Press, 1986.

CELLULAR TENSEGRITY: DEFINING NEW RULES OF BIOLOGICAL DESIGN THAT GOVERN THE CYTOSKELETON. Donald E. Ingber in *Journal of Cell Science,* Vol. 104, No. 3, pages 613–627; March 1993.

MECHANOTRANSDUCTION ACROSS THE CELL SURFACE AND THROUGH THE CYTOSKELETON. Ning Wang, James P. Butler and Donald E. Ingber in *Science,* Vol. 260, pages 1124–1127; May 21, 1993.

GEOMETRIC CONTROL OF CELL LIFE AND DEATH. Christopher S. Chen, Milan Mrksich, Sui Huang, George M. Whitesides and Donald E. Ingber in *Science,* Vol. 276, pages 1425–1428; May 30, 1997.

TENSEGRITY: THE ARCHITECTURAL BASIS OF CELLULAR MECHANOTRANSDUCTION. Donald E. Ingber in *Annual Review of Physiology,* Vol. 59, pages 575–599; 1997.

Burial of Radioactive Waste under the Seabed

Although the notion troubles some environmentalists, the disposing of nuclear refuse within oceanic sediments merits consideration

by Charles D. Hollister and Steven Nadis

On the floor of the deep oceans, poised in the middle of the larger tectonic plates, lie vast mudflats that might appear, at first glance, to constitute some of the least valuable real estate on the planet. The rocky crust underlying these "abyssal plains" is blanketed by a sedimentary layer, hundreds of meters thick, composed of clays that resemble dark chocolate and have the consistency of peanut butter. Bereft of plant life and sparsely populated with fauna, these regions are relatively unproductive from a biological standpoint and largely devoid of mineral wealth.

Yet they may prove to be of tremendous worth, offering a solution to two problems that have bedeviled humankind since the dawn of the nuclear age: these neglected suboceanic formations might provide a permanent resting place for high-level radioactive wastes and a burial ground for the radioactive materials removed from nuclear bombs. Although the disposal of radioactive wastes and the sequestering of material from nuclear weapons pose different challenges and exigencies, the two tasks could have a common solution: burial below the seabed.

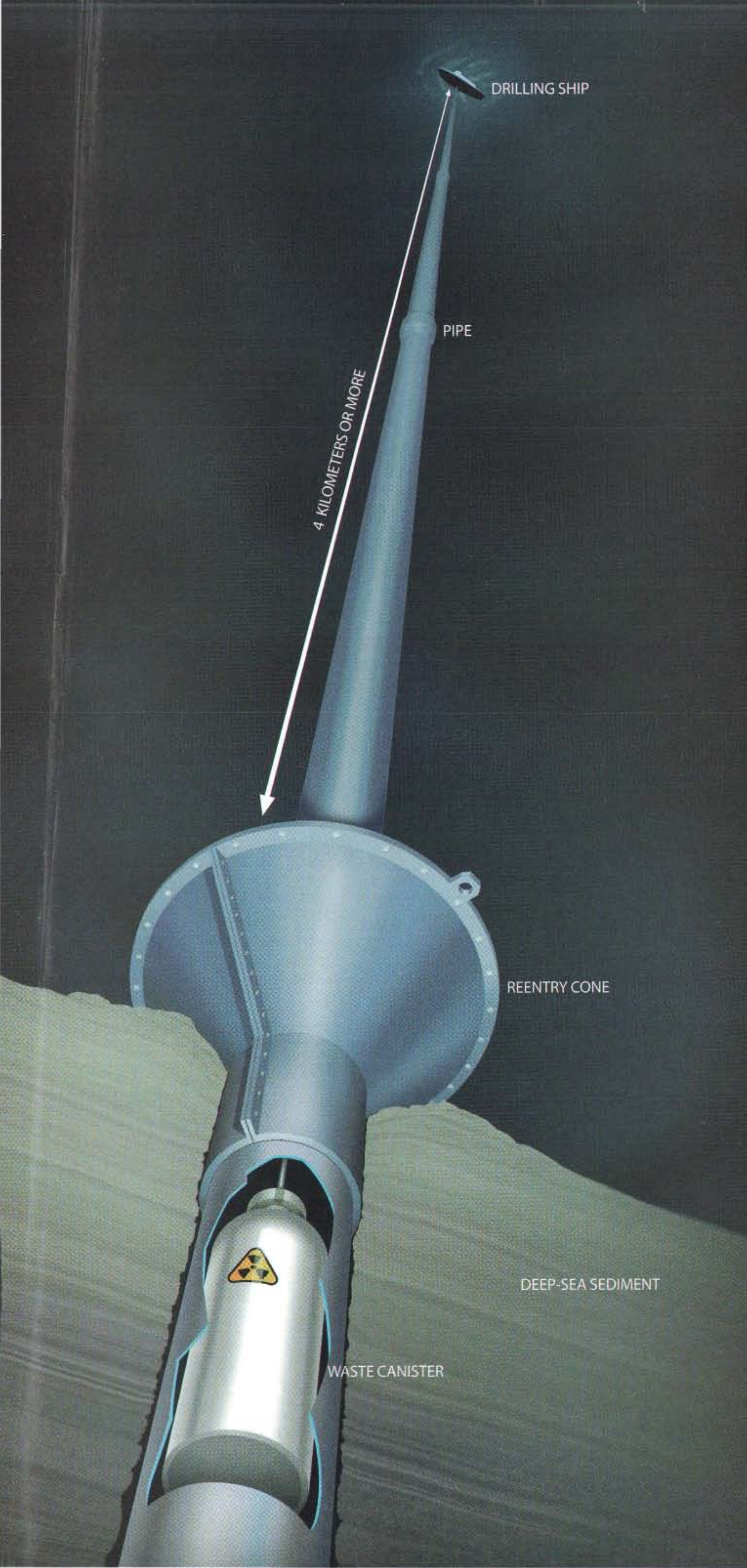
High-level radioactive wastes—in the form of spent fuel rods packed into pools at commercial nuclear power plants or as toxic slurries housed in tanks and drums at various facilities built for the production of nuclear weapons—have been accumulating for more than half a century, with no permanent disposal method yet demonstrated. For instance, in the U.S. there are now more than 30,000 metric tons of spent fuel stored at nuclear power plants, and the amount grows by about 2,000 metric tons a year. With the nuclear waste repository under development at Yucca Mountain, Nev., now mired in controversy and not expected to open before 2015 at the earliest [see "Can Nuclear Waste Be Stored Safely at Yucca Mountain?" by Chris G. Whipple; SCIENTIFIC AMERICAN, June 1996], pressure is mounting to put this material somewhere.

The disposition of excess plutonium and uranium taken from decommissioned nuclear weapons is an even more pressing issue, given the crisis that might ensue if such material were to fall into the wrong hands. The U.S. and Russia have each accumulated more than 100 metric tons of weapons-grade plutonium, and each country should have at least 50 metric tons of excess plutonium, plus hundreds of tons of highly enriched uranium, left over from dismantled nuclear weapons. Preventing terrorists or "rogue states" from acquiring this material is, obviously, a grave concern, given that a metric ton of plutonium could be used to make hundreds of warheads, the precise number depending on the size of the bomb and the ingenuity of the designer.

The Clinton administration has endorsed two separate methods for ridding the nation of this dangerous legacy. Both entail significant technical, economic and political uncertainties. One scheme calls for the surplus weapons plutonium to be mixed with radioactive wastes and molded into a special type of glass (a process called vitrification) or, perhaps, ceramic for subsequent burial at a site yet to be chosen. The glass or ceramic would immobilize the radioactive atoms (to prevent them from seeping into the surrounding environment) and would make deliberate extraction of the plutonium difficult. But the matrix material does not shield against the radiation, so vitrified wastes would still remain quite hazardous before disposal. Moving ahead with vitrification in the U.S. has required construction of a new processing plant, situated near Aiken, S.C. Assuming this facility performs at its intended capacity, each day it will produce just one modest cylinder of glass containing about 20 or so kilograms of plutonium. The projected cost is $1.4 million for each of these glassy logs. And after that considerable expense and effort, someone still has to dispose of the highly radioactive products of this elaborate factory.

The second option would be to combine the recovered plutonium with uranium oxide to create a "mixed oxide" fuel for commercial reactors—although most nuclear power plants in the U.S. would require substantial modification before they could run on such a blend. This alternative measure of consuming mixed-oxide fuels at commercial power plants is technically feasible but nonetheless controversial. Such activities

STEEL PIPE, lowered from a ship on the surface, would be used to drill holes in the deep-sea muds and, later, convey nuclear waste containers for permanent burial—according to the plan envisioned. Mud pumped into the borehole would then seal the nuclear refuse within the clay-rich undersea formation, effectively isolating the radioactive materials.



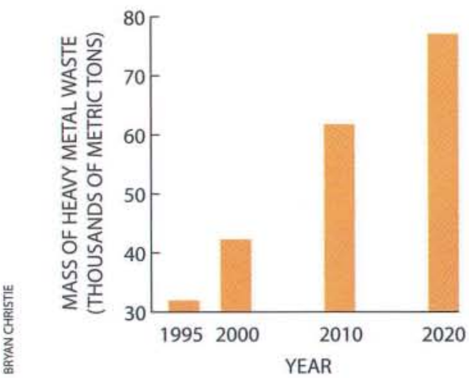
GEORGE RETSECK

would blur the traditional separation between military and civilian nuclear programs and demand heightened security, particularly at mixed-oxide fabrication plants (of which none currently exist in the U.S.), where material suitable for building a nuclear bomb might be stolen. And in the end, mixed-oxide reactors would produce other types of radioactive waste. Hence, neither of the schemes planned for disposing of material from nuclear weapons is entirely satisfactory.

Pressing Problems

For the past 15 years, the operators of nuclear power plants in the U.S. have been paying the Department of Energy in advance for the eventual storage or disposal of their wastes. Even though there is no place yet available to put this radioactive refuse, the courts have ordered the DOE to meet its contractual obligations and begin accepting expended fuel rods from nuclear utilities this year. It is not at all clear what the DOE will do with these materials. One plan supported by the U.S. Senate is to build a temporary storage facility in Nevada near the Yucca Mountain site, but President Bill Clinton opposes this stopgap measure. In any event, the mounting pressure to take some action increases the likelihood of hasty, ill-considered judgments. The best course, in our opinion, would be to do nothing too drastic for now; immediate action should be limited to putting the spent fuel currently residing in cooling ponds into dry storage as needed and trying to stabilize the leaks in high-level-waste containers at weapons sites, while scientists and engineers thoroughly investigate all reasonable means for permanent disposal.

Although some ambitious thinkers have suggested that nuclear waste might one day be launched into space and from there cast into the sun, most people who have studied the problem agree that safety and economy demand that the waste be put permanently underground. Curiously, the search for a suitable nuclear graveyard has been confined almost exclusively to sites on the continents, despite the fact that geologic formations below the world's oceans, which cover some 70 percent of the planet's surface, may offer even greater potential. The disposal of nuclear weapons and wastes below the seabed should not be confused with disposal in the deep-



SPENT REACTOR FUEL will more than double in quantity in the U.S. by the year 2020, even if no new nuclear power plants are built, according to estimates of the Department of Energy (*graph*). Because no procedures for permanent disposal are yet established, the spent nuclear fuel is now stored temporarily at the reactor sites, often in cooling ponds (*above*).

ocean trenches formed at the juncture of two tectonic plates—a risky proposition that would involve depositing waste canisters into some of the most geologically unpredictable places on the earth, with great uncertainty as to where the material would finally reside.

Subseabed disposal, in contrast, would utilize some of the world's most stable and predictable terrain, with radioactive waste or nuclear materials from warheads "surgically" implanted in the middle of oceanic tectonic plates. Selecting sites for disposal that are far from plate boundaries would minimize chances of disruption by volcanoes, earthquakes, crustal shifts and other seismic activity. Many studies by marine scientists have identified broad zones in the Atlantic and Pacific that have remained geologically inert for tens of millions of years. What is more, the clay-rich muds that would entomb the radioactive materials have intrinsically favorable characteristics: low permeability to water, a high adsorption capacity for these dangerous elements and a natural plasticity that enables the ooze to seal up any cracks or rifts that might develop around a waste container. So the exact form of the wastes (for example, whether they are vitrified or not) does not affect the feasibility of this approach. No geologic formations on land are known to offer all these favorable properties.

It is also important to note that disposal would not be in the oceans, per se, but rather in the sediments below. Placing nuclear waste canisters hundreds of meters underneath the floor of the deep ocean (which is, itself, some five or so kilometers below the sea surface) could be accomplished using standard deep-sea drilling techniques. The next step—backfilling to seal and pack the boreholes—is also a routine practice. This technology has proved itself through decades of use by the petroleum industry to probe the continental shelves and, more recently, by members of the Ocean Drilling Program, an international consortium of scientific researchers, to explore deeper locales.

We envision a specialized team of drillers creating boreholes in the abyssal muds and clays at carefully selected locations. These cylindrical shafts, some tens to hundreds of meters deep, would probably be spaced several hundred meters apart to allow for easy maneuvering. Individual canisters, housing plutonium or other radioactive wastes, would then be lowered by cable into the holes. The canisters would be stacked vertically but separated by 20 or more meters of mud, which could be pumped into the hole after each canister was emplaced.

As is the case for disposal within Yucca Mountain, the waste canisters themselves would last a few thousand years at most. Under the seabed, however, the muddy clays, which cling tenaciously to plutonium and many other radioactive elements, would prevent these substances from seeping into the waters above. Experiments conducted as part of an international research program concluded that plutonium (and other transuranic elements) buried in the clays would not migrate more than a few meters from a breached canister after even 100,000 years. The rates of migration for uranium and some other radioactive waste elements need yet to be properly determined. Still, their burial several tens to 100 meters or more into the sediments would most likely buy enough time for the radioactivity of all the waste either to decay or to dissipate to levels below those found naturally in seawater.

The Seabed Working Group, as the now defunct research program was called, consisted of 200 investigators from 10 countries. Led by the U.S. and sponsored by the Nuclear Energy Agency of the Organization for Economic Cooperation and Development, the project ran from 1976 to 1986 at a total cost of about $120 million. This program was an outgrowth of a smaller effort at Sandia National Laboratories that was initiated in response to a suggestion by one of the authors (Hollister), who conceived of the idea of subseabed disposal in 1973.

As part of the international program, scientists extracted core samples of the seabed and made preliminary environmental observations at about half a dozen sites in the northern Atlantic and Pacific oceans. The collected sediments showed an uninterrupted history of geologic tranquillity over the past 50 to 100 million years. And there is no reason to believe that these particular sites are extraordinary. On the contrary, thousands of cores from other midplate locations since examined as part of the Ocean Drilling Program indicate that the sediments that were studied origi-

nally are typical of the abyssal clays that cover nearly 20 percent of the earth. So one thing is clear: although other factors may militate against subseabed disposal, it will not be constrained by a lack of space.

Reviving an Old Idea

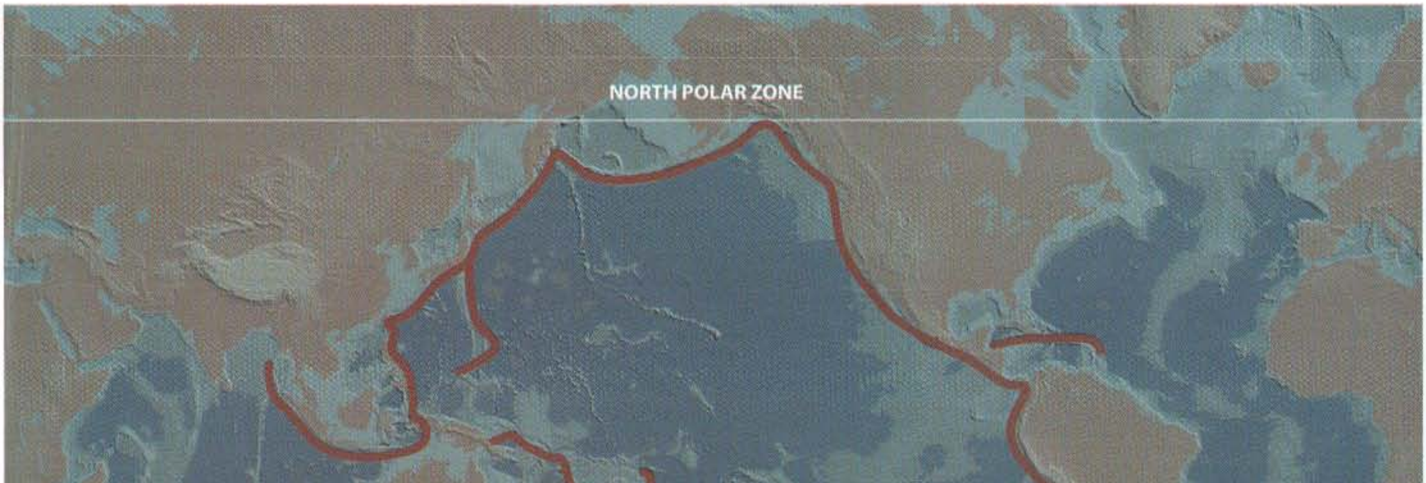
The Seabed Working Group concluded that although a substantial body of information supports the technical feasibility of the concept, further research "should be conducted before any attempt is made to use seabed disposal for high-level waste and spent fuel." Unfortunately, the additional investigations were never carried out because the U.S.—the principal financial backer of this research—cut off all funding in 1986 so that the nation could concentrate its efforts on land-based disposal. A year later the federal government elected to focus exclusively on developing a repository at Yucca Mountain—a shortsighted decision, especially in view of current doubts as to whether the facility will ever open. And even if the Yucca Mountain repository does become operational, it will not be able to handle all the high-level wastes from military and commercial sources that will have accumulated by the time of its inauguration, let alone the 2,000 or more tons of waste each year the nuclear industry will continue to churn out.

At some point, policymakers are going to have to face this reality and start exploring alternative sites and approaches. This view was precisely the conclusion expressed in a 1990 report from the National Academy of Sciences, which said that alternatives to mined geologic repositories, including subseabed disposal, should be pursued—a recommendation that remains absolutely valid today.

Fortunately, most of the experiments needed to assess more fully both the reliability and safety of subseabed disposal have been designed, and in many cases prototype equipment has already been built. One important experiment that remains to be done would be to test whether plutonium and other radioactive elements move through ocean-floor clays at the same rates measured in the laboratory. And more work is required

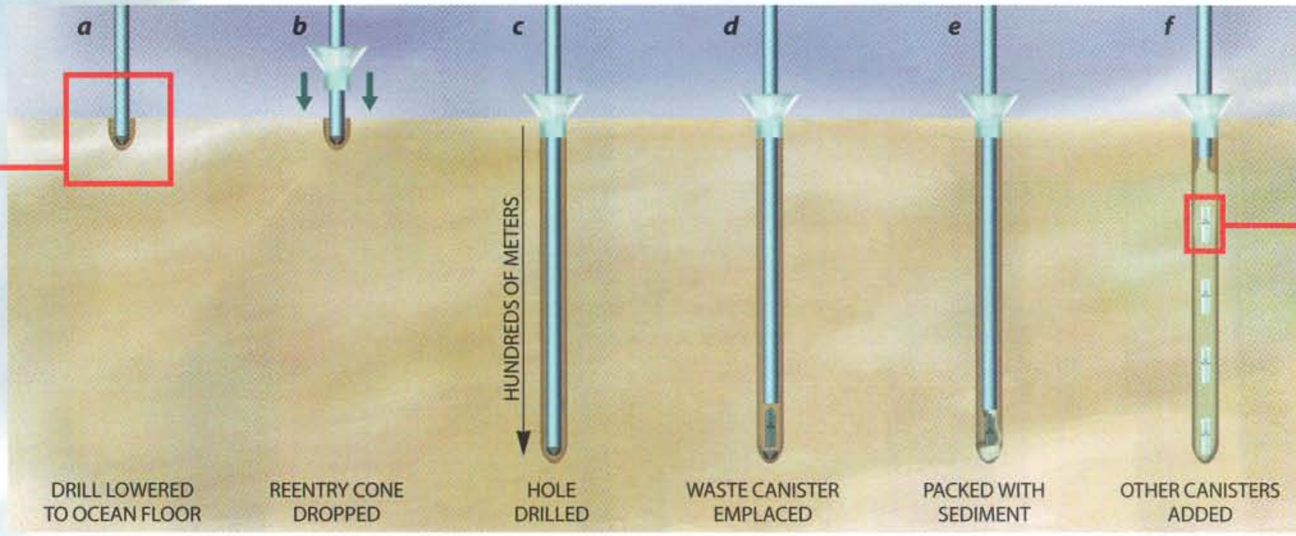
DANIEL HULSHIZER *AP Photo*

DEEP-SEA DRILL SHIP, such as the one used by scientists of the Ocean Drilling Program, could bore holes under the seabed, insert nuclear waste containers and seal them with mud.



WILLIAM F. HAXBY

SEAFLOOR PROVINCES are not all suited for the disposal of nuclear wastes. In searching for candidate areas, scientists would probably eliminate places where the ocean floor is shallower than about four kilometers (*light blue*), because these areas coincide with plate-tectonic spreading centers and are often blanketed by inappropriate types of sediments. They would also rule out other regions of tectonic activity, such as plate collision (*red*) or vulcanism. Polar zones (latitudes higher than 60 degrees) would be discounted because marine sediments there commonly contain coarse rock fragments carried in by icebergs. Even after these and other broad areas (such as around continental rises, where the sediments are thick enough to house valuable quantities of oil or gas) are exempted, vast stretches of seafloor still offer ample possibilities for burying nuclear wastes (*dark blue*).



to learn how the heat given off by fuel rods (caused by the rapid decay of various products of nuclear fission) would affect surrounding clays.

Research is also needed to determine the potential for disturbing the ecology of the ocean floor and the waters above. At present, the evidence suggests that mobile, multicellular life-forms inhabit only the top meter or so of the abyssal clays. Below a meter, there appear to be no organisms capable of transporting radioactive substances upward to the seafloor. Still, scientists would want to know exactly what the consequences would be if radioactive substances diffused to the seafloor on their own. Researchers would want to ascertain, for instance, exactly how quickly relatively soluble carriers of radioactivity (such as certain forms of cesium and technetium) would be diluted to background levels. And they would want to be able to predict the fate of comparatively insoluble elements, such as plutonium.

So far no evidence has been found of currents strong enough to overcome gravity and bring claybound plutonium particles to the ocean surface. Most likely the material would remain on the seabed, unless it were carried up by creatures that feed on the sea bottom. That prospect, and all other ways that radioactive materials might rise from deep-sea sediment layers to surface waters, warrant further investigation. The transportation of nuclear waste on the high seas also requires careful study. In particular, procedures would need to be developed for recovering lost cargo should a ship carrying radioactive materials sink or accidentally drop its load.

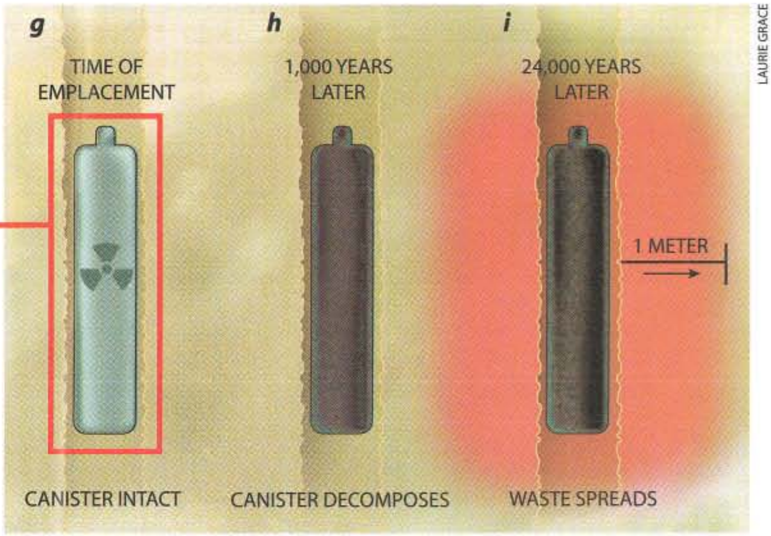
Engineers would probably seek to design the waste containers so that they could be readily retrieved from the bottom of the ocean in case of such a mishap or, in fact, even after their purposeful burial. Although subseabed disposal is intended to provide a permanent solution to the nuclear waste crisis, it may be necessary to recover material such as plutonium at some point in the future. That task would require the same type of drilling apparatus used for emplacement. With the location of the waste containers recorded at the time of interment, crews could readily guide the recovery equipment to the right spot (within a fraction of a meter) by relying on various navigation aids. At present, no nonnuclear nation has the deep-sea technology to accomplish this feat. In any event, performing such an operation in a clandestine way would be nearly impossible. Hence, the risk that a military or terrorist force could hijack the disposed wastes from under the seabed would be negligible.

All Eggs in One Basket

The overall cost of a concerted program to evaluate subseabed disposal might reach $250 million—admittedly a large sum for an oceanographic research endeavor. But it is a relatively modest price to pay considering the immense benefits that could result. (As a point of comparison, about $2 billion has already been spent on site evaluation at Yucca Mountain, and another billion or two will probably be needed to complete further studies and secure regulatory approval. No actual construction, save for exploratory tunneling, has yet begun.) Yet no nation seems eager to invest in any research at all on subseabed disposal, despite the fact that it has never been seriously challenged on technical or scientific grounds. For example, a 1994 report by the National Academy of Sciences that reviewed disposal options for excess weapons plutonium called subseabed disposal "the leading alternative to mined geologic repositories" and judged implementation to be "potentially quick and moderate to low cost." But the academy panel stopped short of recommending the approach because of the anticipated difficulties in gaining public acceptance and possible conflicts with international law.

Convincing people of the virtues of subseabed burial is, admittedly, a tough sell. But so is the Yucca Mountain project, which is strongly opposed by state officials and residents of Nevada. Subseabed disposal may turn out to be easier to defend among the citizenry than land-based nuclear waste repositories, which are invariably subject to the "not in my backyard" syndrome.

In any case, subseabed disposal is certain to evoke significant opposition in the future should the idea ever go from being a remote possibility to a serious contender. Oddly, the concept has recently come under direct fire, even though no research has been done in more than a decade. A bill introduced last year in the House of Representatives contains a provision that would prohibit the subseabed disposal of spent nuclear fuel or high-level radioactive waste as well as prevent federal funding for any activity relating to subseabed dis-



SEAFLOOR DISPOSAL would require a series of operations. After lowering a long, segmented drill pipe several kilometers to the ocean floor (*a*), technicians on the ship would put a "reentry cone" around the pipe and drop the device to the bottom (*b*). (The cone could guide another drill pipe to the hole later, should the need arise.) Turning and advancing the pipe (to which a bit is attached) would drill it into the ocean floor (*c*). By releasing the bit, the drillers could then lower a waste canister within the pipe using an internal cable (*d*). After packing that part of the hole with mud pumped down through the pipe (*e*), they would emplace other canisters above it (*f*). The topmost canister would reside at least some tens of meters below the seafloor (*g*). In about 1,000 years the metal sheathing would corrode, leaving the nuclear waste exposed to the muds (*h*). In 24,000 years (the radioactive half-life of plutonium 239), plutonium and other transuranic elements would migrate outward less than a meter (*i*).

posal—apparently including research. The intent of part of this bill is reasonable: subseabed disposal should be illegal until outstanding safety and environmental issues can be resolved. But it makes absolutely no sense to ban research on a technically promising concept for the disposal of weapons plutonium and high-level nuclear wastes.

Subseabed disposal faces serious international hurdles as well. In 1996, at a meeting sponsored by the International Maritime Organization, contracting parties to the so-called London Dumping Convention voted to classify the disposal of nuclear material below the seabed as "ocean dumping" and therefore prohibited by international law. This resolution still awaits ratification by the signatory nations, and the outcome may not be known for several years. But regardless of how that vote goes, we submit that "ocean dumping" is a wholly inappropriate label. It makes as much sense as calling the burial of nuclear wastes in Yucca Mountain "roadside littering."

Yet even assuming that the nations involved uphold the ban, the bylaws of the London convention would allow for subseabed disposal to be reviewed in 25 years, an interval that would provide sufficient time to complete a comprehensive appraisal of this disposal method. The 25-year moratorium could be wisely spent addressing the remaining scientific and engineering questions as well as gaining a firmer grasp of the economics of this approach, which remains one of the biggest uncertainties at present. In our most optimistic view, the legal infrastructure already established through the London convention could eventually support a program of subseabed disposal on an international basis.

A parallel effort should be devoted to public education and discussion. Right now there seems to be a strong aversion among some environmental advocates to any action at all to address the nuclear waste problem—and a solution that involves the oceans seems particularly unpalatable. But it makes no sense to dismiss the possibility of disposal in stable suboceanic formations—which exceed the land area available for mined repositories by several orders of magnitude—simply because some people object to the concept in general. It would be much more prudent to base a policy for the disposal of nuclear waste, whose environmental consequences might extend for hundreds of thousands of years, on sound scientific principles.

Barring a miraculous technical breakthrough that would allow radioactive elements to be easily transformed into stable ones or would provide the safe and economic dispatch of nuclear wastes to the sun, society must ultimately find somewhere on the planet to dispose of the by-products of the decades-long nuclear experiment. Americans in particular cannot responsibly pin all hopes on a single, undersized facility in a Nevada mountainside. They owe it to future generations to broaden their outlook and explore other possibilities, including those that involve the thick, muddy strata under the sea. SA

The Authors

CHARLES D. HOLLISTER and STEVEN NADIS began regular discussions about subseabed disposal of nuclear wastes in 1995. Hollister, who is a vice president of the corporation of Woods Hole Oceanographic Institution, has studied deep-sea sediments for the past three decades. He continues to do research in the department of geology and geophysics at Woods Hole. Nadis graduated from Hampshire College in 1977 and promptly joined the staff of the Union of Concerned Scientists, where he conducted research on nuclear power, the arms race and renewable energy sources. He then wrote about transportation policy for the World Resources Institute. Currently a Knight Science Journalism Fellow at the Massachusetts Institute of Technology, Nadis specializes in writing about science and technology.

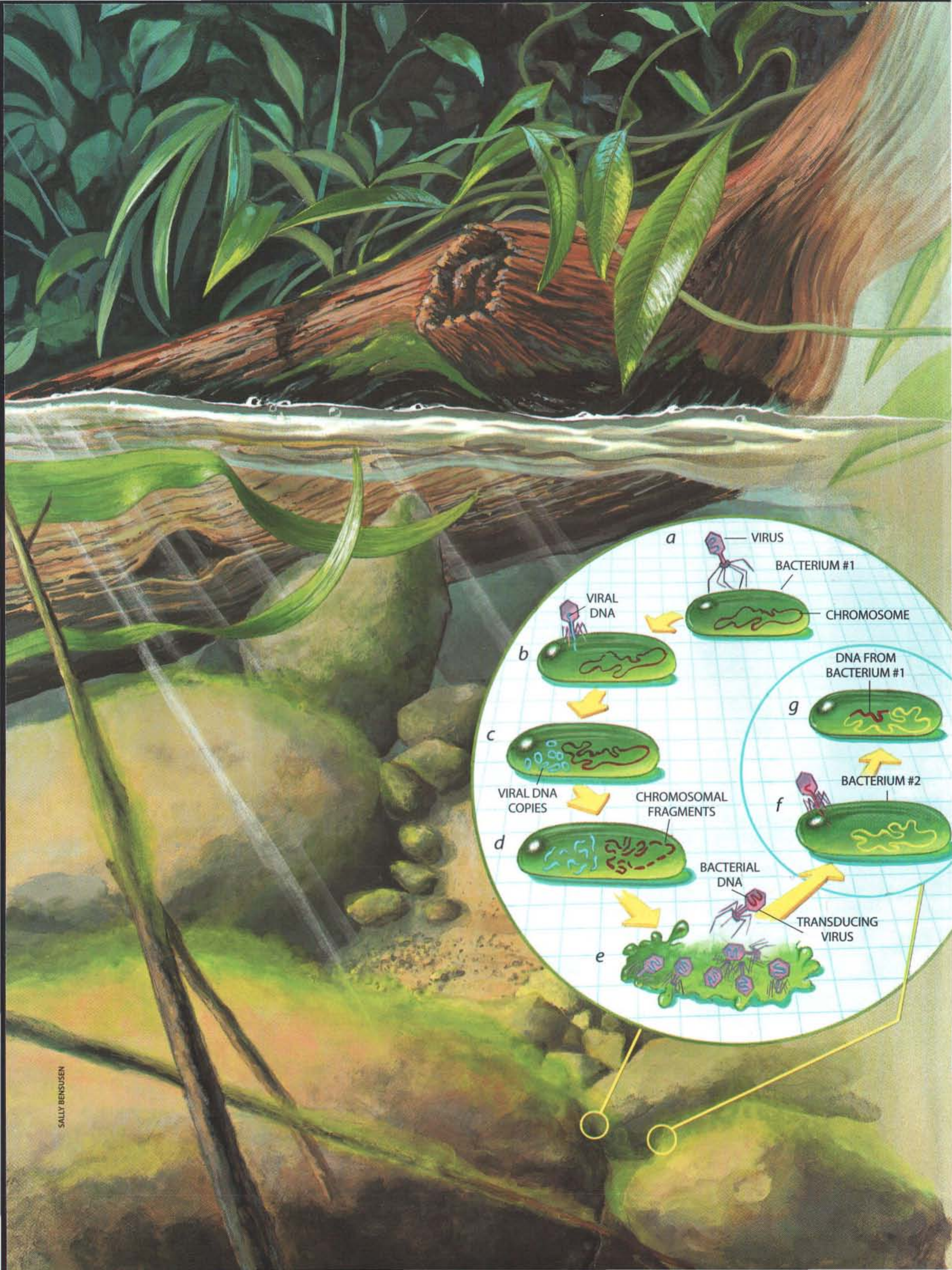
Further Reading

SUBSEABED DISPOSAL OF NUCLEAR WASTES. C. D. Hollister, D. R. Anderson and G. R. Heath in *Science*, Vol. 213, pages 1321–1326; September 18, 1981.

MANAGEMENT AND DISPOSITION OF EXCESS WEAPONS PLUTONIUM. National Research Council. National Academy Press, 1994.

THE SUB-SEABED SOLUTION. Steven Nadis in *Atlantic Monthly*, pages 28–39; October 1996.

RADIOACTIVE WASTE: THE SIZE OF THE PROBLEM. John F. Ahearne in *Physics Today*, Vol. 50, No. 6, pages 24–29; June 1997.


a
VIRUS
BACTERIUM #1
CHROMOSOME
VIRAL DNA
b
DNA FROM BACTERIUM #1
g
c
VIRAL DNA COPIES
CHROMOSOMAL FRAGMENTS
BACTERIUM #2
f
d
BACTERIAL DNA
TRANSDUCING VIRUS
e
SALLY BENSUSEN

Bacterial Gene Swapping in Nature

Genes travel between independent bacteria more often than once was assumed. Study of that process can help limit the risks of releasing genetically engineered microbes into the environment

by Robert V. Miller

In the early 1980s, as scientists were perfecting techniques for splicing foreign genes into bacteria, some investigators began suggesting ways to use the technology to benefit the environment. For instance, they proposed that genetically engineered bacteria might be deployed for such tasks as cleaning oil spills or protecting crops from predation and disease. But the enterprise, known as environmental biotechnology, soon came under fire.

Then, as now, the proposals elicited concern that the altered microbes might run amok or that their genes would hop unpredictably to other organisms—a phenomenon termed "horizontal" gene transfer (to distinguish it from the "vertical" transfer occurring between a parent and its offspring). Such activities, it was feared, might somehow irreparably harm the environment, animals or people. Some observers even issued dire warnings that the unnatural organisms would destroy the earth. No longer were tabloids worried about attacks by "killer tomatoes" from outer space; now the danger was homegrown—genetically altered microorganisms that would eat the environment.

Unfortunately, at the time, biologists had little solid information on which to base responses. They knew almost nothing about the fate of genetically engineered microbes in nature and about the propensity of innate or introduced bacterial genes to migrate to new hosts. That paucity of data is now being remedied, thanks to unprecedented cooperation between genetic researchers and microbial ecologists, who study microorganisms in their normal habitats.

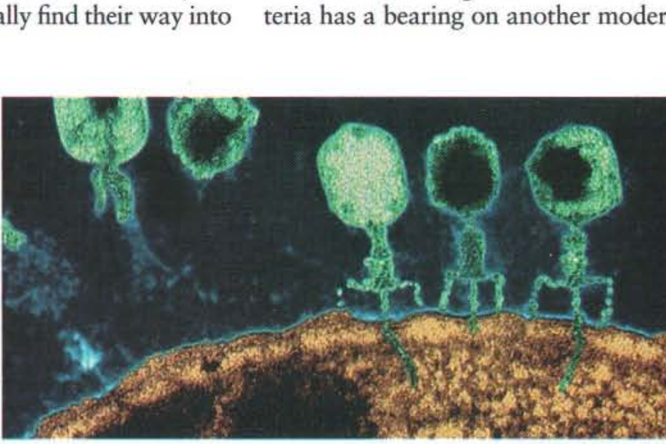
Today at least two strains of genetically engineered bacteria have gained approval (for agricultural use) by the U.S. Environmental Protection Agency, and dozens of field trials have been conducted. Those trials and more general investigations of gene transfer between bacteria in their natural habitats indicate that genetically manipulated bacteria themselves are unlikely to proliferate out of control. They tend to be fragile and to die out relatively quickly instead of persisting indefinitely; for that reason, their genes probably do not have much opportunity to spread.

Yet under certain circumstances, the genes can potentially find their way into other bacteria or even into other types of organisms. A key to the safe release of the microbes, then, is to identify the conditions that will encourage or deter specific bacteria from transferring their genes to other organisms—a challenge my laboratory at Oklahoma State University and others are pursuing vigorously. With such information in hand, biologists can select bacteria that will be least likely to exchange genes with other organisms in the particular site being "treated." As an example, for release into a lake, biotechnologists might be able to choose a bacterial species that does not readily exchange its genes in water.

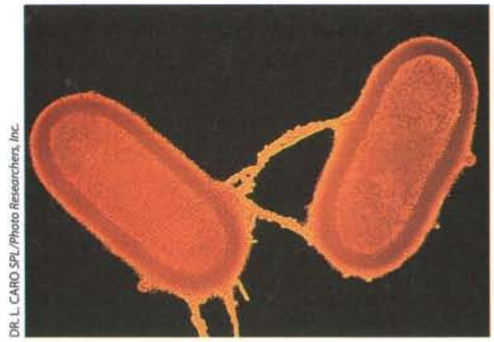
Scientists cannot yet compile an exacting list of which bacteria are best for any given application. The combined research has revealed a great deal, however, about the propensity for the three most common forms of horizontal gene transfer—transduction, conjugation and transformation—to occur in nature.

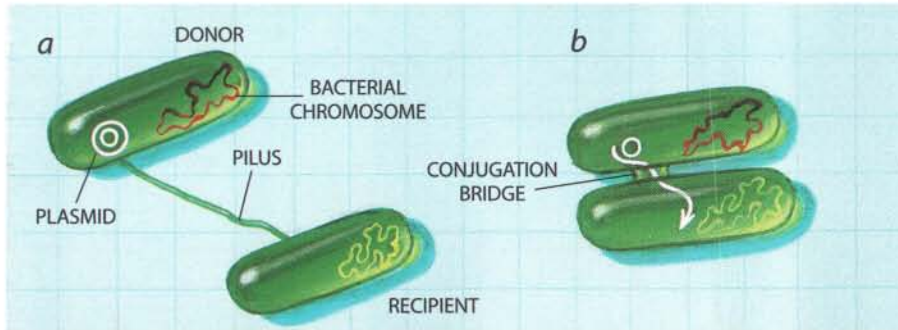
Those findings will be the focus of this article, but I should note that improved understanding of the conditions that facilitate horizontal gene transfer in bacteria has a bearing on another modern

GENE TRANSFER by a process called transduction has been found to occur between bacteria living in the slimy layer, or epilithon, of neighboring, submerged rocks (*left*) and elsewhere. Transduction takes place after a bacteriophage (bacteria-infecting virus) attaches to a bacterial cell and injects its DNA into the cell (*a* and *b at left; micrograph at right*). Inside the bacterium, the injected DNA replicates (*c*), and the bacterium's chromosome breaks up (*d*). Normally, the viral DNA is packaged into new viral particles, which burst from the host (*e*). But during transduction, some particles instead take up bacterial DNA (containing bacterial genes) and deliver it to a second bacterium (*f*), which incorporates the hijacked DNA into its chromosome (*g*).



OLIVER MECKES MPI-Tübingen/Photo Researchers, Inc.





BACTERIA CAN TRANSFER PLASMIDS, circles of DNA, through conjugation. In gram-negative bacteria, a donor cell extends one or more projections—pili—that attach to a recipient cell and pull the two bacteria together (*micrograph* and *a*). Next a bridge (essentially a pore) forms between the cells. Then one strand of plasmid DNA passes into the recipient bacterium (*b*), and each single strand becomes double-stranded again (*c*). With the transfer complete, the bacteria separate (*d*). Conjugation in gram-positive bacteria (*not shown*) is similar, but the cells are drawn together by chemical signaling instead of by a pilus.

concern: rising resistance to antibiotics in disease-causing bacteria. It turns out that bacteria, which are single-cell organisms, often donate antibiotic-resistance genes to other species of bacteria in the human body. Understanding when and how this transfer occurs should help investigators develop strategies for blocking it.

On a more theoretical level, the discovery that horizontal gene transfer is fairly common in nature suggests that, over evolutionary time, the process could have contributed to the great genetic diversity now evident in bacteria. Some findings even indicate that genes have been exchanged among the three major groups of biological life: bacteria, eukaryotes (animals, plants, fungi and protozoa) and archaea (ancient microbes having some properties of both bacteria and eukaryotes). Current information suggests that gene transfer has occurred from bacteria to eukaryotes, from bacteria to archaea and especially from eukaryotes to bacteria. Horizontal gene exchange may thus have influenced the evolution of any number of life-forms.

A Fateful Fishing Trip

My own involvement in exploring horizontal gene transfer in nature dates back to the spring of 1976, when I was an assistant professor at the University of Tennessee at Knoxville. I was then strictly a geneticist interested in how living cells work. I did realize that certain bacteria could naturally transmit genes from one mature bacterial cell to another. From my perspective, though, horizontal gene transfer was of interest only insofar as it provided a practical way to introduce new genes, and thus new traits, into cells being studied in the laboratory.

A fishing trip one Saturday afternoon with Gary Sayler, another young assistant professor at the university, suddenly altered my narrow view. As we sat in our boat, Sayler, a microbial ecologist, asked me whether I thought much genetic exchange was occurring among the bacteria in the lake below. I assumed bacterial cells would be dispersed in the water and would have relatively little contact with one another. I therefore guessed that the rate of gene transfer was low. When pressed, though, I had to admit that I was not well versed in the scientific papers on horizontal gene transfer in nature.

The following Monday, confident that the literature would be extensive, I strolled to the library in search of a more authoritative answer. Several hours later I emerged shocked and disappointed; virtually nothing was known.

Sayler, however, was elated. He had just developed a chamber for studying organisms living in freshwater. We could test the device and begin to fill a scientific gap by measuring the amount of transduction taking place at our fishing hole. Over the following fall and spring seasons, we carried out the first studies demonstrating that transduction can occur in freshwater.

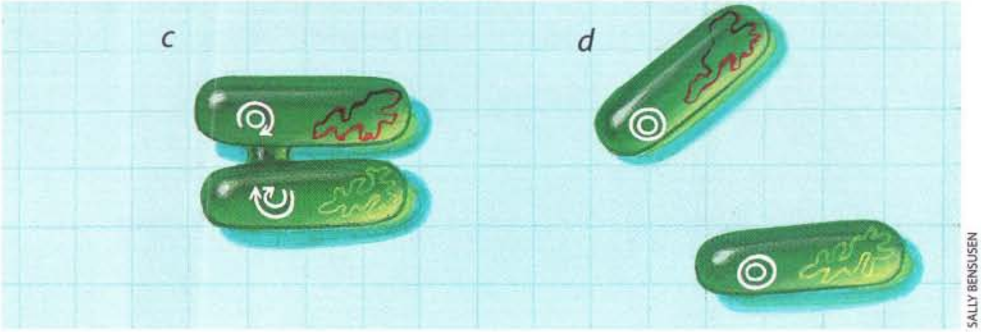
When we published the results, in 1978, we were certain others would be as intrigued as we were and that our paper represented the first in a long series of research projects on bacterial gene exchange in nature. Yet at the time, no funding agencies shared our vision. By 1985, though, worry over the release of genetically engineered bacteria in the environment had changed all that. Hence, Sayler and I—and others—began playing catch-up and exploring the potential for horizontal gene transfer to occur in a variety of settings.

Conjugation Is Confirmed

Conjugation was the first mechanism of gene transfer studied extensively as a way bacteria might disseminate genetic material in nonlaboratory arenas. It was identified in 1946, when Joshua Lederberg and Edward Tatum of Yale University found that the intestinal bacterium *Escherichia coli* uses a process resembling sex to exchange circular DNA elements that are now called plasmids.

Plasmids contain genes but are separate from the bacterial chromosome, which is larger and contains the genes needed for bacterial reproduction. (Chromosomes can sometimes be exchanged by conjugation as well but only in extremely rare circumstances.) Plasmids often carry genes that enhance the chances of survival in hostile circumstances. For example, in addition to including the genes needed for their own replication and transfer, they often harbor genes for proteins that enable bacteria to evade destruction by antibiotics, to degrade toxic compounds such as polychlorinated biphenyls (PCBs) or to transform mercury or other heavy metals into less noxious forms.

For historical reasons, microbiologists divide bacteria into gram-negative and gram-positive types, depending on whether the bacteria retain a particular stain. Laboratory work has shown that in gram-negative bacteria, which do not keep the stain, conjugation begins when a donor bacterium attaches an appendage called a pilus to a recipient bacterium that displays a receptor for the pilus; then the pilus retracts, drawing togeth-



er the donor and recipient. Generally, many donors extend pili at about the same time, and several donor cells can converge on a recipient at once. Consequently, extension of pili causes bacterial cells to aggregate into clusters. After aggregation occurs, bridges, or pores, form between donor and recipient cells, and plasmids pass through the bridges from the donors to the recipients.

Some pili can promote aggregation of bacterial cells in liquid and on solid surfaces; others can stimulate aggregation efficiently only on solid surfaces. Such differences imply that researchers who wanted to introduce a genetically engineered gram-negative bacterium into an aquatic environment might be wise to select a species having pili that induce aggregation on solid surfaces only.

Conjugation in gram-positive bacteria does not involve pili. In advance of conjugation a would-be recipient of new genes secretes substances that prompt potential donors to produce proteins, often called clumping factors, able to bring bacterial cells together. When the cells associate, they form the pores needed for DNA transfer. Hence, if investigators were to choose a recombinant gram-positive bacterium for release into an area containing other gram-positive bacteria, they might reduce the risk of gene transfer in the setting by altering the bacterium so that it was unable to manufacture any clumping factor.

In general, gram-negative and gram-positive bacteria, which can occur together in natural aquatic and terrestrial environments, exchange plasmids exclusively with members of their own group; many restrict exchange to their own species. But some "promiscuous" plasmids can transfer DNA between very unrelated species: between gram-negative and gram-positive bacteria and even from bacteria to yeast cells and plants. Obviously, then, bacteria that carry promiscuous plasmids would be poor choices for use outside the laboratory.

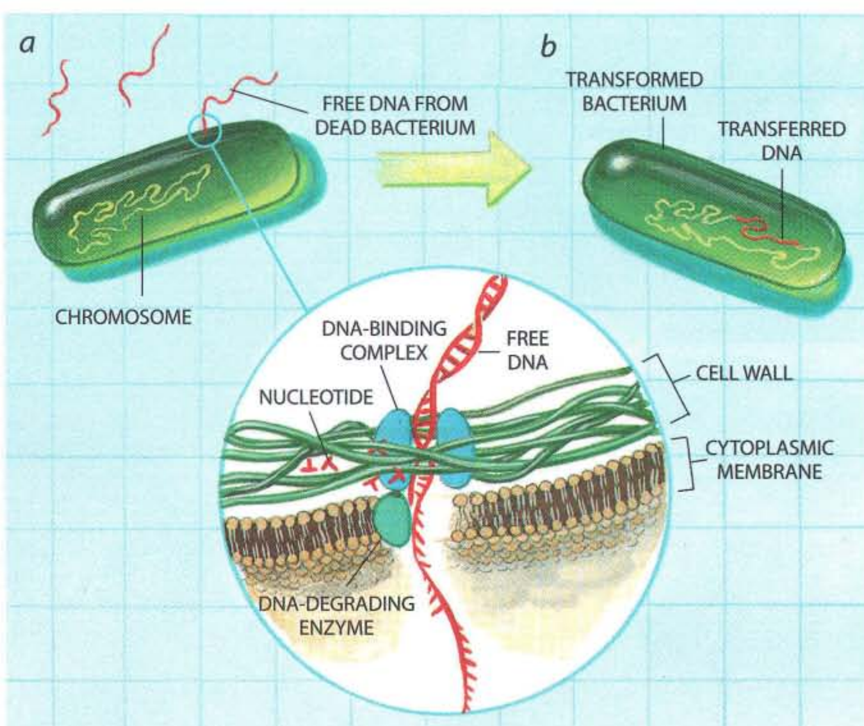
But does conjugation, in fact, occur frequently enough in nature to justify the precautions suggested by bench research? Since the advent of environmental biotechnology in the 1980s, researchers have demonstrated that conjugation does take place in many natural spheres, including in water, on land and in various plants and animals.

Key Conjugation Studies

Notably, in one series of studies, John C. Fry, Martin J. Day and their colleagues at the University of Wales demonstrated that gene transfer through conjugation can occur between bacteria in freshwater environments. The researchers found that conjugation can enable a laboratory strain of *Pseudomonas aeruginosa* to pick up a plasmid that naturally provides resistance to mercury toxicity in bacteria that inhabit the polluted river Taft, near Cardiff, Wales. *P. aeruginosa* is a common soil and freshwater bacterium that can cause respiratory and urinary tract infections in humans whose immune defenses are weakened.

The investigators began by mutating a *P. aeruginosa* gene; this manipulation caused the gene to generate an abnormal version of the protein specified by the intact gene. The altered protein would later serve as a marker for keeping track of any bacterial cells put into the river. Having revised the *P. aeruginosa* gene, the team introduced the marked bacteria into the nutrient-rich, slimy layers, or epilithons, covering submerged stones in the river. (The stones were wrapped in a very fine filter material to prevent the bacteria from escaping.)

After 24 hours, the group retrieved the stones and examined the epilithons for marked *P. aeruginosa* cells that had received a mercury-resistance plasmid



BACTERIUM UNDERGOING TRANSFORMATION (*a*) picks up free DNA released from a dead bacterial cell. As DNA-binding complexes on the bacterial surface take up the DNA (*detail*), enzymes break down one strand into nucleotides; meanwhile the other strand may integrate into the bacterium's chromosome (*b*). Transformation, shown here in a gram-positive bacterium, can also occur in gram-negative species, but the process is not especially common in either group.

Some Environments Where Horizontal Gene Transfer Has Been Documented

	TRANSDUCTION	CONJUGATION	TRANSFORMATION
TERRESTRIAL ENVIRONMENTS	Soil, plant surfaces	Soil, plant surfaces	Soil
WATERY ENVIRONMENTS	Lakes, oceans, rivers, sewage in treatment facilities	Lakes, oceans, marine sediments, rivers, epilithon (slime layer) on river stones, sewage in treatment facilities	Marine sediments, rivers, epilithon on river stones
INSIDE ORGANISMS	Shellfish, mice	Plants, insects, chickens, mice, humans	Plants, insects, mice

JENNIFER C. CHRISTIANSEN

from the naturally occurring *P. aeruginosa* population on the rocks. Only between one in 10,000 and one in a billion of the introduced *P. aeruginosa* had acquired a plasmid, but such transfer had undeniably taken place. The work also yielded the useful information that such factors as water temperature, acidity level and concentration of nutrients affect conjugation frequency.

In many studies, environmental factors have been found to modulate conjugation differently in nature than in the laboratory. For example, in the experiments of Fry, Day and their colleagues, conjugation occurred at six to 18 degrees Celsius—temperatures too low to support conjugation in laboratory strains of bacteria. These unexpected results mean that conjugation has to be studied in nature if researchers are to specify accurately the conditions that keep it to a minimum.

Based on the work of Fry, Day and others, scientists now conclude that although bacteria do use conjugation to transfer genetic information in many different environments, genetically altered plasmids probably pose little danger. Plasmids slow the growth rates of bacteria and are usually eliminated if there is no advantage to an organism in keeping them. For instance, if a genetically manipulated plasmid carrying the mercury-resistance trait found its way into an organism living outside of a mercury-polluted locale, the new host would soon get rid of the plasmid.

Further, plasmids are seldom, if ever, integrated into bacterial chromosomes. Thus, even if they travel to a new bacterial host, they do not become a stable part of that host's genome; chromosomes are invariably copied and distributed to new generations of bacterial cells whenever a parent cell reproduces itself, but plasmids are not reproduced consistently when cells divide. Nevertheless, to virtually eliminate the chance that a gene put into a genetically engineered bacterium will spread via conjugation, biotechnologists considering using recombinant bacteria in nature have opted to insert the genes into chromosomes instead of plasmids.

Transformation Risk Is Minimal

Although conjugation was the first mechanism of bacterial gene transfer to be studied extensively in the environment, it was not the earliest to be identified. The study of gene transfer among bacteria began in 1928, when British bacteriologist Frederick Griffith observed that nonvirulent pneumococcal bacteria became virulent when injected into mice along with dead virulent pneumococcus. Griffith concluded that the initially nonvirulent bacteria picked up a "transforming" agent from the dead virulent bacteria and thus became potent enough to kill the mice. That transforming agent is now known to be DNA that was released into the surrounding medium when the dead bacteria fell apart. A gene is said to be successfully exchanged through transformation if it is taken in as part of a full plasmid or if a fragment of DNA containing the gene becomes integrated into a recipient's chromosome.

Natural transformation in both gram-negative and gram-positive bacteria requires that the freed DNA remain stable and that potential recipient cells become competent to take it up. That is, the recipients must display specialized surface proteins that bind to the DNA and internalize it.

Until recently, researchers assumed that transformation would not occur in most places, because free DNA would not be stable in soil or water. But studies by Michael Lorenz and Wilfried Wackernagel of the University of Öldenburg in Germany, Guenther Stotzky of New York University and others have demonstrated that free DNA can become stable by associating with soil components and that this DNA can be taken up by competent cells. Newer investigations indicate that plasmid DNA has at times been transferred by transformation in river water and in the epilithon on river stones. (I know of no observations, however, indicating that chromosomal genes have been transferred by transformation in aquatic or terrestrial environments.)

Still, few researchers believe gene exchange by transformation is likely to ensue readily if genetically engineered bacteria are put into the environment.

Natural transformation seems to occur only between cells of the same species, and relatively few bacterial species are capable of becoming competent for transformation; biotechnologists can avoid using these species for genetic engineering. Further, although dead bacteria may at times release large quantities of DNA that is absorbed by certain other bacteria, the DNA often is not assimilated as intact genes. John Paul of the University of South Florida and his colleagues have demonstrated that high concentrations of cell-free bacterial DNA can appear in estuarine waters after dawn, when many bacteria typically die and release their genetic material. Yet in laboratory experiments the researchers found that most released DNA salvaged by living bacteria is broken down promptly into its constituent parts for use in the synthesis of new DNA; the genes contained in the free DNA are rarely kept intact.

From Bacteria to Virus and Back

Unlike transformation, the third form of horizontal gene transfer—transduction—can occur in a wide range of bacteria. In transduction, bacteriophages (viruses that infect bacteria) pick up genetic material from one bacterial cell and deposit it in another.

As part of their life cycle, bacteriophages attach to bacteria and inject their DNA. This DNA then serves as a blueprint for making more copies of the bacteriophage, which burst from the infected bacterium and go on to infect other cells. At times, however, some of the new particles carry bacterial instead of viral DNA. Indeed, bacteriophages are capable of transferring whole plasmids and pieces of chromosomes between hosts. (Full chromosomes are too big to fit into bacteriophages.) Laboratory experiments indicate that some bacteriophages can apparently infect several species and even genera of bacteria, suggesting they might broadcast bacterial genes well beyond the locale where they first took up the genes.

Because transduction could potentially lead to broad dispersion of a foreign gene, my colleagues and I concentrate on its study. Initially, we looked for transduction by collecting bacteria in the kind of environmental containment chamber invented by Sayler. That chamber consisted of a clear plastic tube capped at both ends with filters that allowed water and nutrients in but prevented bacteria from leaking out. These days we use gas-permeable plastic bags for our experiments.

On the basis of our studies, we have proposed a model for the transduction-mediated dispersal of genetic material from an introduced bacterium to other bacteria in nature. Simply put, our model states that when a bacterium carrying a new gene enters a habitat, bacteriophages infect that cell and create more bacteriophage particles. If any particles end up containing the new gene, that gene can be passed on to the indigenous bacterial population. This model is equally applicable to the transduction of chromosomal and plasmid DNA. Recently we have sought to prove that this scenario is in fact carried out in freshwater. We have isolated bacteria and bacteriophages from various lakes and have demonstrated that bacteria do share genetic information by transduction in those settings.

Many microbiologists originally thought transduction would not be an important means of gene exchange in the environment, because it requires viruses and bacteria—both of which were thought to be present in low concentrations—to interact. But my co-workers and I have recently found bacteriophages in very high concentrations (often 100 billion virus particles per milliliter) in fresh and marine waters. These observations have caused a reevaluation of the frequency of interactions, including transduction, that occur between bacteriophages and their hosts.

Even so, current understanding suggests that transduction of genes carried by genetically engineered bacteria in the environment is probably severely limited by a number of factors. One is that most bacteriophages infect only one species of bacteria, not many different species. Another is that most bacteriophages in the wild infect only bacteria that are native to the bacteriophage's habitat—not the laboratory strains of bacteria used in genetic engineering. Eventually, molecular biologists should also be able to equip genetically altered bacteria with traits that limit the ability of the bacterial DNA to move to and survive in another species; such restrictions are already under development.

Biologists can now manipulate the genetic makeup of almost any organism. In addition to being applied to the creation of recombinant bacteria, the technology is being used by farmers to grow genetically altered crops that resist various ills [see "Making Rice Disease-Resistant," by Pamela C. Ronald; SCIENTIFIC AMERICAN, November 1997]. The collected studies of bacteria in their native habitats suggest that genetically engineered organisms can be put into the environment safely and that the most important consideration is whether the genetically altered organism will do the job asked of it. Still, caution is warranted. As understanding of horizontal gene transfer expands, environmental biotechnologists should gain the information needed to reduce the risks to the barest minimum.

The Author

ROBERT V. MILLER, who holds a Ph.D. from the University of Illinois, has been professor and head of the department of microbiology and molecular genetics at Oklahoma State University since 1991. He began his academic career in 1974 at the University of Tennessee at Knoxville and in 1980 joined the faculty of the Stritch School of Medicine at Loyola University in Chicago. From 1987 to 1993 he served on the Biotechnology Science Advisory Committee of the U.S. Environmental Protection Agency, during which time he helped to establish the agency's policy for releasing genetically engineered microbes into the environment.

Further Reading

GENE TRANSFER IN THE ENVIRONMENT. Edited by Stuart B. Levy and Robert V. Miller. McGraw-Hill, 1989.

GENETIC INTERACTIONS AMONG MICROORGANISMS IN THE NATURAL ENVIRONMENT. Edited by E.M.H. Wellington and J. D. van Elsas. Pergamon Press, 1992.

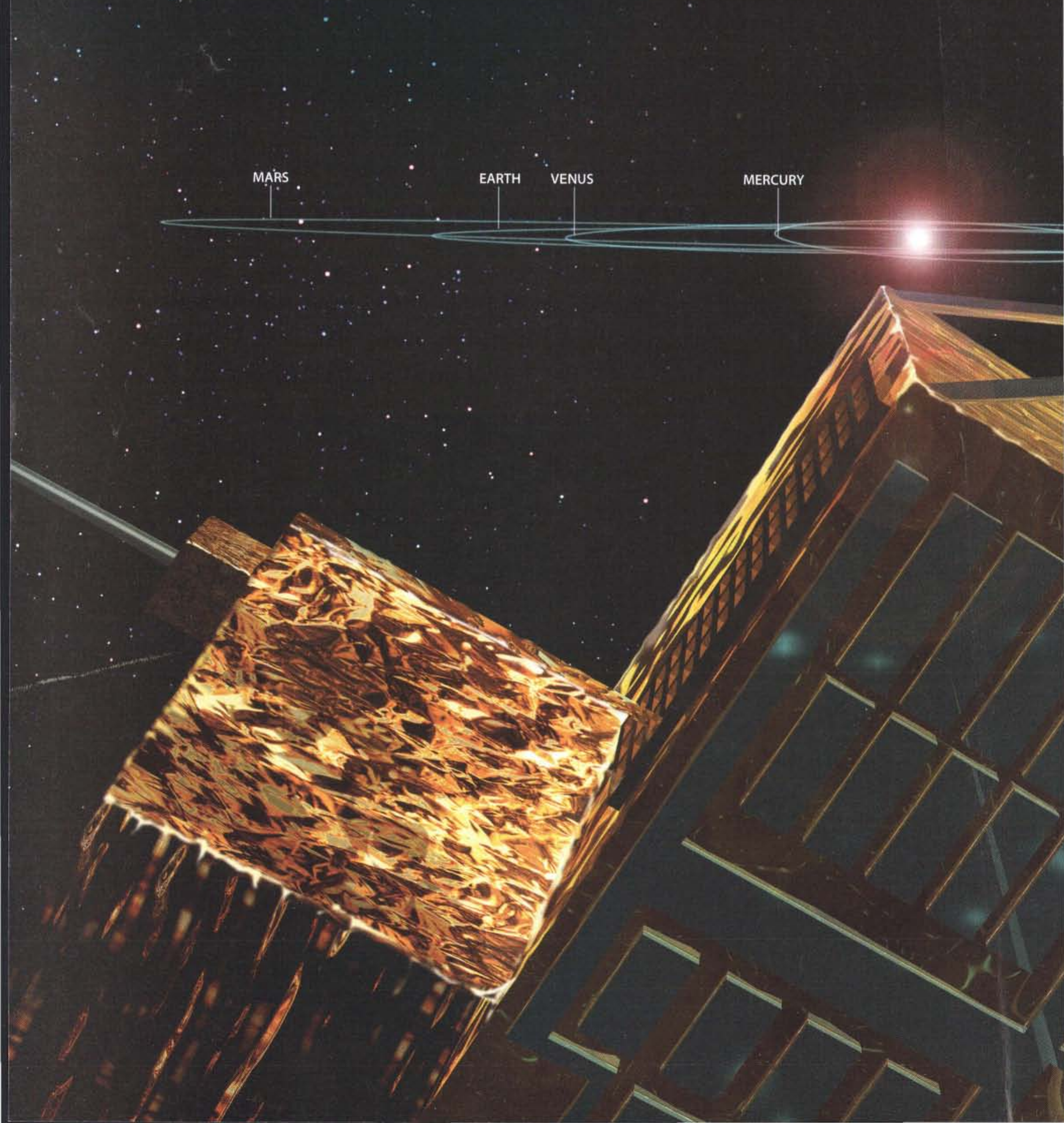
RELEASE OF GENETICALLY ENGINEERED AND OTHER MICRO-ORGANISMS. J. C. Fry and M. J. Day. Cambridge University Press, 1992.

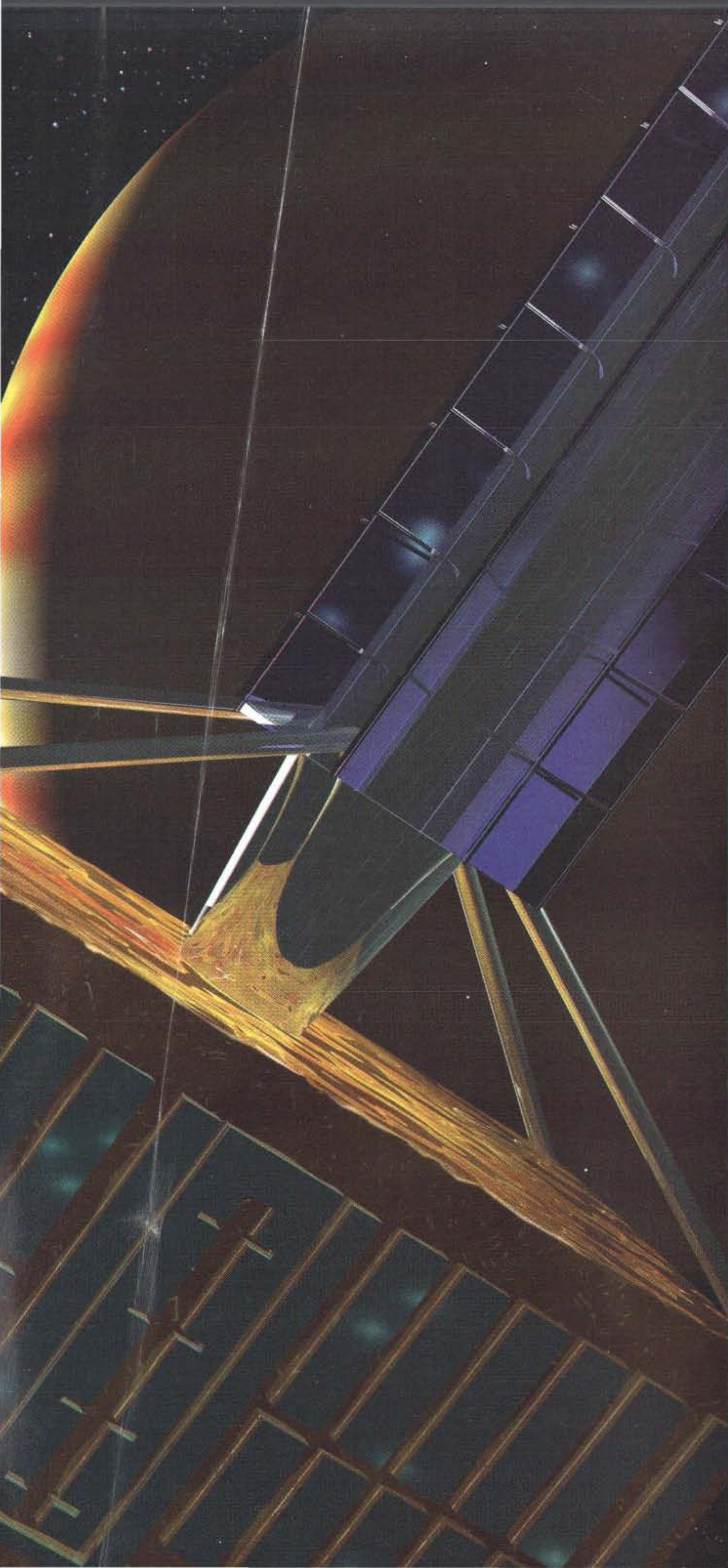
STRATEGIES AND MECHANISMS FOR FIELD RESEARCH IN ENVIRONMENTAL BIOREMEDIATION. Robert V. Miller and Jeanne S. Poindexter. American Academy of Microbiology, Washington, D.C., 1994.

HORIZONTAL GENE TRANSFER. Edited by M. Syvanen and C. Kado. Chapman and Hall (in press).

The Ulysses Mission

The first space probe to be sent on a "polar" trajectory has made some remarkable discoveries on its first orbit around the sun





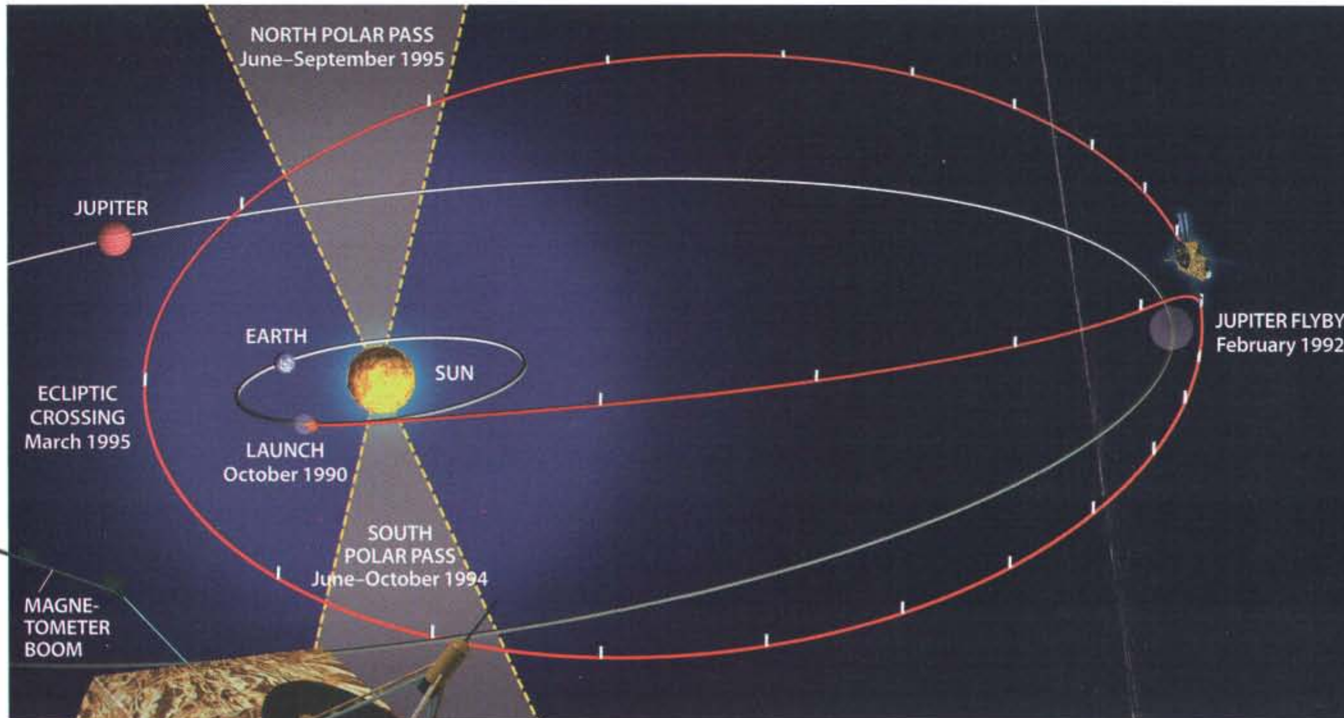
by Edward J. Smith
and Richard G. Marsden

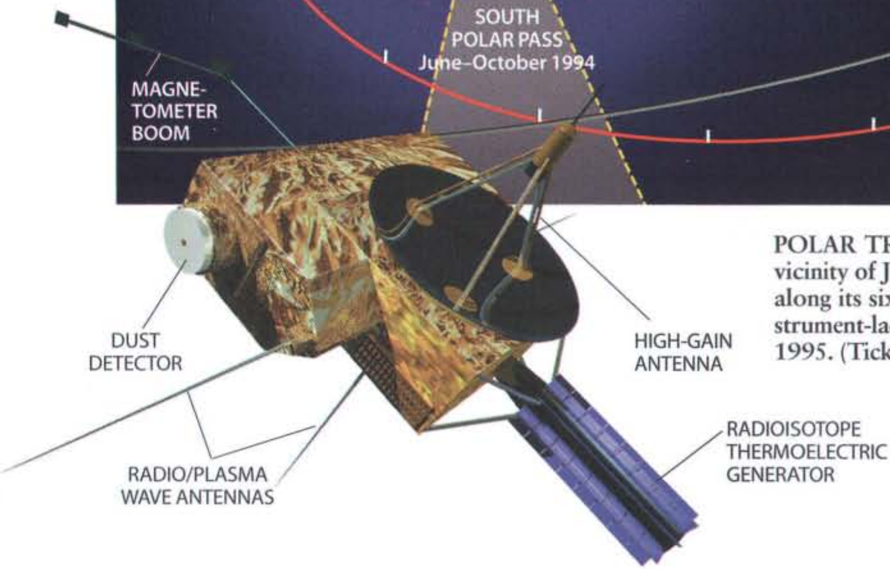
Although explorers have been traveling around the world for the past 500 years, it was not until the 20th century that a few hardy souls first trudged across the frozen wastes of the Arctic and Antarctic to reach the North and South poles. Curiously, exploration of the solar system has followed a similar pattern. For much of the past four decades, the scientific probes sent into space stayed relatively close to the equatorial plane of the sun, which contains the orbits of Earth and other planets. But a few years ago a single craft, Ulysses, ventured out of that thin zone and into the "polar regions" of interplanetary space.

The reasons researchers waited so long to investigate this realm have more to do with the vagaries of spaceflight than a lack of attention. Indeed, scientific interest in making such a journey has been quite keen. Astronomers have known for decades that the sun is surrounded by a diaphanous outer atmosphere (called the solar corona) that extends past the orbit of Earth. And they realized that the gases in the tails of comets always point away from the sun because they are pushed by the corona as it streams rapidly outward, a flow called the solar wind. Until recently, however, scientists have been unable to sense how the material emanating from around the poles of the sun courses through the interplanetary vastness.

The solar wind has profound effects. Were it absent, the flotsam of interstellar space—gas, dust, magnetic fields and isolated particles—would drift close to the sun and waft through the void between the planets. The solar wind clears away the bulk of this interstellar debris, pushing it well beyond the orbit of the outermost planets. Until quite recently, the immense domain carved out in this way, a region called the heliosphere, was largely unexplored. Astronomers knew

ENCOUNTER WITH JUPITER allowed the Ulysses craft to lose the angular momentum it had inherited from Earth. The swooping trajectory around the gas giant sent the probe "southward," out of the planes of planets and into a steeply inclined orbit around the sun.





POLAR TRAJECTORY of Ulysses (*above*) began as it left the vicinity of Jupiter early in 1992. Because the probe moves fastest along its six-year-long orbit when it is closest to the sun, the instrument-laden craft (*left*) could pass over both poles in 1994 and 1995. (Tick marks show position of craft at 100-day intervals.)

especially little about the higher-latitude parts of this bubble of solar influence.

So the scientific justification for sending a probe out of the plane of Earth's orbit around the sun (the ecliptic) was clear—but the means were not. To break from the ecliptic, a spacecraft must somehow lose the momentum it receives from its launch platform, Earth, which travels around the sun at a speed of 30 kilometers per second. Given this initial high velocity, even the most energetic rockets available cannot send a probe directly on a trajectory over the poles of the sun. The only way to achieve such an orbit is to swoop around a large planet, namely, Jupiter, using that maneuver to cancel excess momentum inherited from Earth and to propel the spacecraft into an orbit angled far from the ecliptic.

At first, many scientists worried that this tactic would not prove practical, because the intense radiation belts surrounding Jupiter threatened to damage the sensitive electronics carried by interplanetary probes. But two spacecraft, Pioneer 10 and 11, flew by Jupiter in the early 1970s and demonstrated that they could weather those storms of energetic particles. Their success opened the way for a polar mission around the sun, subsequently named Ulysses in honor of the mythical Greek warrior, who also traversed unexplored territory.

Although the National Aeronautics and Space Administration and the European Space Agency decided to join forces on the project in 1977, the launch of Ulysses did not take place until 1990. The intervening years were occupied by the design, fabrication and testing of the spacecraft—and by a series of side battles. For example, the original plan to construct separate European and American craft had to be revamped because of concerns about the cost. So a single probe was built by the European Space Agency; it was to be launched by NASA and to carry both European and American instruments. But a disastrous setback occurred in 1986, the year Ulysses was to be placed on board the space shuttle. A few months before the scheduled launch, the designated shuttle, *Challenger,* blew up shortly after liftoff. That catastrophe grounded all shuttles for two years, causing a large backlog to develop. So after nine years of preparation, Ulysses had another four years of waiting to start on its journey.

Fire and Wind

Well before the Ulysses mission began, observations from Earth (or from orbit) had shown that the solar wind does not shoot uniformly from all points on the sun. Some of the most important sources of solar wind are the bright loops that reach high above the surface of the sun in the vicinity of the solar equator. These structures, called streamers, follow the magnetic field of the sun, which extends well above the surface with looping lines of force that commonly begin in one hemisphere and end in the other. Another important feature of the solar corona, characterized by a conspicuous absence of visible ma-

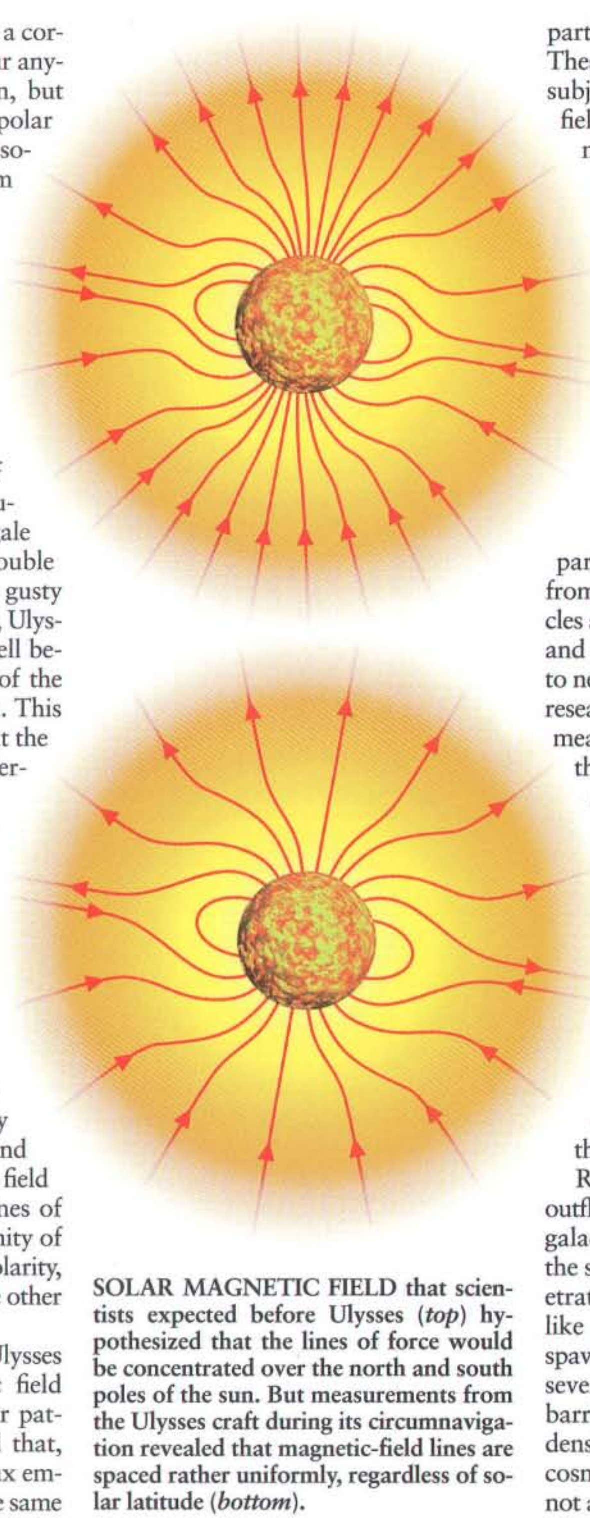
terial, is called, naturally enough, a coronal hole. Coronal holes can occur anywhere on the surface of the sun, but they are usually present on the polar caps. These holes emit streams of solar wind that move outward from the sun comparatively quickly.

Measurements from Ulysses have now helped answer some key questions about the solar wind. After Ulysses swung around Jupiter and started traveling "southward," it passed into a region of high-speed wind issuing from the coronal hole at the south pole of the sun. The solar-wind instruments on Ulysses detected a gale blowing at a steady clip, with double the average speed of the more gusty low-latitude breezes. Interestingly, Ulysses encountered this fast wind well before it had reached the latitude of the southern coronal hole on the sun. This finding indicated immediately that the polar wind must expand considerably after leaving the sun.

Such a large expansion was unexpected. But some other measurements from Ulysses provided an explanation. Previously, scientists had measured the magnetic field of the sun indirectly by examining how certain elements in the solar atmosphere absorb light of different wavelengths. Using this property (called Zeeman line splitting), they found that the magnetic field around the sun was usually much like the field that envelops Earth: magnetic lines of force are concentrated in the vicinity of two magnetic poles of opposite polarity, one located near the north and the other near the south pole of rotation.

Astronomers anticipated that Ulysses would show that the magnetic field along its orbit followed a similar pattern. Instead the probe revealed that, far from the sun, the magnetic flux emanating outward has essentially the same density at all latitudes. The scientists involved concluded that the expansion of the solar wind coming from the pole must be caused by magnetic forces pushing the wind toward the equator, which then act to spread the lines of magnetic flux more uniformly.

The magnetic field and the solar wind are linked this closely because the wind consists of charged particles. (The solar corona is so hot—about one million kelvins—that neutral atoms release negatively charged electrons, leaving positively charged ions behind.) But both the hot corona and solar wind shed from it are electrically neutral overall, because they are made up of equal numbers of positive charges from the ions and negative charges from the electrons. Despite their mutual attraction, the ions and electrons in the solar wind do not recombine—the density of material is sufficiently low that the chance of two particles coming together is remote. These charged particles are, however, subject to the influence of magnetic fields: in general, the charges cling to magnetic-field lines, circling them in tight orbits. But the magnetic field is also affected by the charged particles in the solar wind. Field lines are pushed and swayed by motions of the solar wind as if they were strands of seaweed caught up in shifting ocean currents.



SLIM FILMS

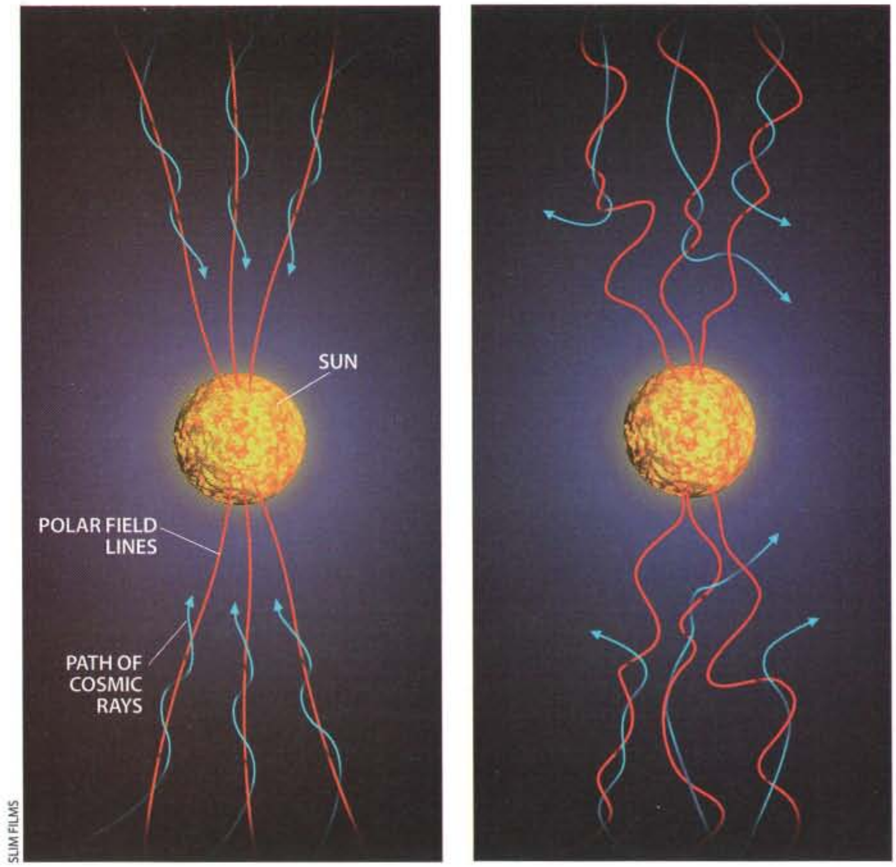
SOLAR MAGNETIC FIELD that scientists expected before Ulysses (*top*) hypothesized that the lines of force would be concentrated over the north and south poles of the sun. But measurements from the Ulysses craft during its circumnavigation revealed that magnetic-field lines are spaced rather uniformly, regardless of solar latitude (*bottom*).

Galactic Intruders

Scientists have known for many years that not all the charged particles in interplanetary space come from the sun. Some of the other particles are atoms stripped of their electrons and accelerated elsewhere in the galaxy to nearly the speed of light. Earthbound researchers, who have long been able to measure the more energetic fraction of these particles as they bombard the atmosphere, named the high-speed intruders cosmic rays. The earliest spacecraft measurements of cosmic rays, obtained nearly four decades ago, showed that rays with lower energies than those recorded near the surface of Earth also exist in abundance. Scientists had discovered that the solar system was, in fact, awash in a variety of particles—coming, it seemed, from all over the galaxy.

Researchers soon realized that the outflow of solar wind must prevent some galactic cosmic rays from approaching the sun. So only a portion of them penetrates to the inner heliosphere, where, like salmon swimming upstream to spawn, they must overcome increasingly severe obstacles. What exactly are the barriers in "empty" space? The low densities of material indeed ensure that cosmic rays and solar-wind particles do not actually collide. After the solar wind leaves the vicinity of the sun, however, it carries part of the solar magnetic field along with it. So incoming rays are subject to the forces that magnetic fields exert on electrically charged particles in motion.

Such forces cause cosmic rays to wrap around the magnetic-field lines as they simultaneously drift along the field direction. The circling rays can also encounter magnetic waves, which propagate along the magnetic-field lines in a



COSMIC-RAY ACCESS to polar regions was thought to be enhanced by the smoothness of the magnetic field there (*left*), because those charged particles could simultaneously move inward along the field lines as they gyrated around them. But Ulysses revealed that these polar magnetic-field lines are in reality folded and kinked (*right*). These irregularities, which are of approximately the same size as the radius of particle gyration, impede the flow of cosmic rays toward the sun.

manner resembling the fluttering of a flag. These waves cause the direction of the magnetic field to shift abruptly, thereby impeding the flow of charged particles. In effect, a cosmic ray headed toward the sun is like a swimmer trying to enter the ocean in the presence of strong surf.

Before the Ulysses mission, astronomers speculated that cosmic rays traveling inward over the poles of the sun might penetrate the heliosphere more easily than those that followed more equatorial routes. There were two principal reasons for this surmise. First, because charged particles follow a helical path along magnetic-field lines, they had expected the shorter, straighter lines of force connecting with the poles to be excellent conduits into the inner heliosphere. Second, some researchers believed waves and other disturbing changes in field direction would be minimal, because the solar wind from polar coronal holes flows comparatively smoothly.

Measurements from Ulysses, however, showed that cosmic rays were only slightly more abundant over the poles of the sun than they were over the equator. Again, unforeseen aspects of the magnetic field provide an explanation: Ulysses found waves rippling through the polar magnetic field, opposing the passage of cosmic rays toward the polar caps. Such disturbances can deflect the path of cosmic-ray particles during their journey through the heliosphere. To many scientists' astonishment, Ulysses showed that the cosmic rays reaching the inner heliosphere are homogenized by the tumultuous magnetic field as efficiently as if they were part of a milkshake.

Getting Up to Speed

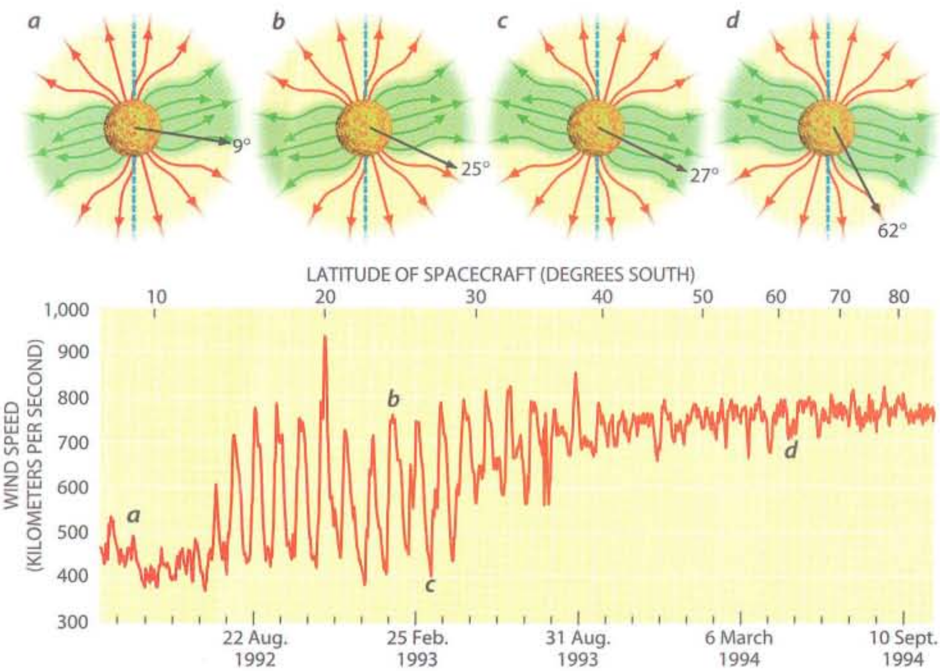
Distinct from galactic cosmic rays are several types of rapidly moving particles that originate inside the heliosphere. Astronomers call them solar energetic particles. Although similar in composition to ions in the solar wind, these particles move considerably faster. In fact, they move far too swiftly to have gained their high energies simply from heating. One possible explanation for these fast-moving ions is that they are sped up by a process similar to that which occurs in particle accelerators called cyclotrons. The charged particles injected into a cyclotron are trapped inside the machine by a strong magnetic field about which they spiral, while gaining energy from an oscillating electrical field.

Of course, nature operates somewhat differently from a highly engineered cyclotron. Strong electrical and magnetic fields arise in space only in particular circumstances, such as when speedy bursts of solar wind meet more sluggish flows ahead of them. In that case, a curved front of high pressure forms, creating large magnetic waves that propagate both forward and backward. These magnetic waves gradually steepen (just as ocean waves do when they approach the beach) and develop into shock waves, thin surfaces across which properties of the solar wind are known to change abruptly.

Measurements returned from spacecraft before Ulysses' journey demonstrated that such shock fronts can accelerate particles to high speeds. That knowledge explained why energetic particles tend to appear with clocklike regularity in the vicinity of Earth, typically twice each solar rotation. Because the magnetic axis of the sun is typically canted somewhat toward the ecliptic, slow-moving solar wind from near the equator of the sun alternates with fast wind from first one and then the other polar cap, forming shock fronts in the process.

Ulysses encountered concentrations of energetic particles accompanying such shock complexes many times while it was en route to Jupiter. But after the spacecraft left low latitudes and reached the region of fast wind from the polar caps, it met no more shock fronts, because the steady flow of the fast wind prevented shocks from forming. Yet surprisingly, the probe continued to record regular bursts of energetic particles at high latitudes. Scientists are still trying to figure out why these rapidly moving particles appear regularly in regions of space that contain no such shocks.

The occurrence of some other types of solar energetic particles also requires more research. When magnetic fields of



SLIM FILMS

SOLAR-WIND SPEED measured by Ulysses varied with latitude of the spacecraft (*black arrows*) and orientation of the magnetic poles of the sun. While Ulysses remained at low solar latitudes (*a*), it encountered only slow, equatorial winds (*green*). At somewhat higher southern latitudes, Ulysses ran into fast, polar winds (*yellow*) when the sun rotated its south magnetic pole toward the probe (*b*) and into slow winds when this pole was rotated away (*c*). Once Ulysses had reached a polar position, it measured fast winds continuously (*d*).

opposite directions are brought together, a situation that arises commonly close to the sun, the two opposing fields cancel, and the energy that was originally in the magnetic fields is given up to charged particles nearby. The composition of certain energetic particles detected indicates that they indeed came from low in the solar atmosphere, where field annihilation is frequent. But exactly how these particles were accelerated there remains to be worked out.

Another type of particle accelerated within the heliosphere also exists. Because the compositions of these speeding particles were quite different from other types of low-energy cosmic rays, scientists dubbed them anomalous cosmic rays. Anomalous cosmic rays have an unusual history. They begin their lives as uncharged atoms of interstellar gas (typically helium, nitrogen or oxygen) that drift serenely into the heliosphere. Because these atoms are electrically neutral, they can move freely through the magnetic-field lines that bar most other particles from the inner heliosphere. Those atoms that pass close to the sun, however, can become ionized by solar radiation or by rare collisions with solar-wind ions.

An ion created in this way is immediately picked up by the surrounding magnetic field and joins the general flow away from the sun. Ulysses identified many different types of such "pickup ions" for the first time. These observations and the improved understanding of the evolution of pickup ions inside the heliosphere should reveal how many of their parent atoms populate interstellar space, information of special interest to numerous astrophysicists.

Before the Ulysses mission, the acceleration of pickup ions into anomalous cosmic rays was thought to occur only at the so-called termination shock of the heliosphere, a fixed boundary where the fast outward flow of the solar wind slows abruptly and becomes hotter. But Ulysses demonstrated that traveling shock fronts well inside the termination shock also accelerate pickup ions.

The prevalence of such shock fronts, and indeed most phenomena recorded by Ulysses during its first polar tour around the heliosphere, is affected by the well-known 11-year cycle of solar activity. By good fortune, the timing of the launch and the path that Ulysses took brought the craft over both poles in 1994 and 1995 when the sun was in a quiescent phase; conditions at the polar caps of the sun were, presumably, at their simplest. When Ulysses passes over the poles again in 2000 and 2001, the sun will be at a maximum level of activity.

The team of scientists working with Ulysses is eager to see what changes ensue. The spacecraft still functions well and sends measurements back to Earth continuously as it circles around the sun. And although much has been learned already, a great deal of information about the sun and heliosphere remains to be discovered as this scientific odyssey continues. SA

The Authors

EDWARD J. SMITH and RICHARD G. MARSDEN each began work in preparation for the Ulysses mission two decades ago. Smith earned a doctorate from the University of California, Los Angeles, in 1959 and two years later joined the Jet Propulsion Laboratory in Pasadena, Calif., where he is currently a member of the earth and space sciences division. He specializes in measuring magnetic fields and electromagnetic waves in space, an enterprise that has involved him with many space missions. Marsden received his doctorate in physics from Imperial College London in 1976 and that year started work on Ulysses as a research fellow at the European Space Agency, where he joined the Ulysses team permanently in 1981. His main research concerns cosmic rays and other energetic particles in space.

Further Reading

THE HIGH LATITUDE HELIOSPHERE. Edited by R. G. Marsden. Kluwer Academic Publishers, 1995.

ULYSSES: SOLAR SOJOURNER. R. G. Marsden and E. J. Smith in *Sky and Telescope,* Vol. 91, No. 3, pages 24–31; March 1996.

More information on the Ulysses mission can be found at http://ulysses.jpl.nasa.gov/ and at http://helio.estec.esa.nl/ulysses/welcome.html on the World Wide Web.

Lise Meitner and the Discovery of Nuclear Fission

by Ruth Lewin Sime

One of the discoverers of fission in 1938, Meitner was at the time overlooked by the Nobel judges. Racial persecution, fear and opportunism combined to obscure her contributions

When scientists first recognized, in late 1938, that a neutron could split an atom's core, the discovery came as a complete surprise. Indeed, no physical theory had predicted nuclear fission, and its discoverers had not the slightest foreknowledge of its eventual use in atomic bombs and power plants. That much of the story is undisputed.

The question of who deserved credit for the breakthrough, however, has long been debated. Physicist Lise Meitner and two chemists, Otto Hahn and Fritz Strassmann, conducted a four-year-long investigation that resulted in the discovery of fission in their laboratory in Berlin. Meitner fled Nazi Germany in 1938 to escape the persecution of Jews, and soon after, Hahn and Strassmann reported the discovery. Meitner and her nephew, Otto R. Frisch, published the correct theoretical interpretation of fission a few weeks later. But the 1944 Nobel Prize in Chemistry was awarded to Hahn alone.

That Strassmann did not get the Nobel with Hahn is probably because he was the junior investigator on the team, and Nobel committees tend to favor senior scientists. But Meitner and Hahn held equal professional standing. Why was she excluded? Hahn offered what became the standard account, which was uncritically accepted for many years. According to him, the discovery had relied solely on chemical experiments that were done after Meitner left Berlin. She and physics, he maintained, had nothing to do with his success, except perhaps to delay it.

Strassmann, who was very much in Hahn's shadow, disagreed. He insisted that Meitner had been their intellectual leader and that she remained one of them through her correspondence with Hahn, even after she left Berlin. The available documents support Strassmann's view. Scientific publications show that the investigation that led to the discovery of fission was intensely interdisciplinary. Questions from nuclear physics initiated the work. Data and assumptions from both chemistry and physics guided and misguided their progress. And private letters reveal that Meitner made essential contributions until the very end.

By any normal standards of scientific attribution, the Nobel committees should have recognized her influence. But in Germany the conditions were anything but normal. The country's anti-Jewish policies forced Meitner to emigrate, separated her from her laboratory and prohibited her from being a co-author with Hahn and Strassmann in reporting the fission result. Because of political oppression and fear, Hahn distanced himself and fission from Meitner and physics soon after the discovery took place. In time, the Nobel awards sealed these injustices into scientific history. Recently released documents show that the Nobel committees did not grasp the extent to which the result relied on both physics and chemistry, and they did not recognize that Hahn had distanced himself from Meitner not on scientific grounds but because of political oppression, fear and opportunism.

Other factors also served to marginalize Meitner, including her outsider status as a refugee in Sweden, a postwar unwillingness in Germany to confront Nazi crimes, and a general perception—held much more strongly then than it is now—that women scientists were unimportant, subordinate or wrong. Publicly, Meitner said little at the time. Privately, she described Hahn's behavior as "simply suppressing the past," a past in which they had been the closest of colleagues and friends. She must have believed that history would be on her side. Fifty years later, it is.

Investigating Uranium

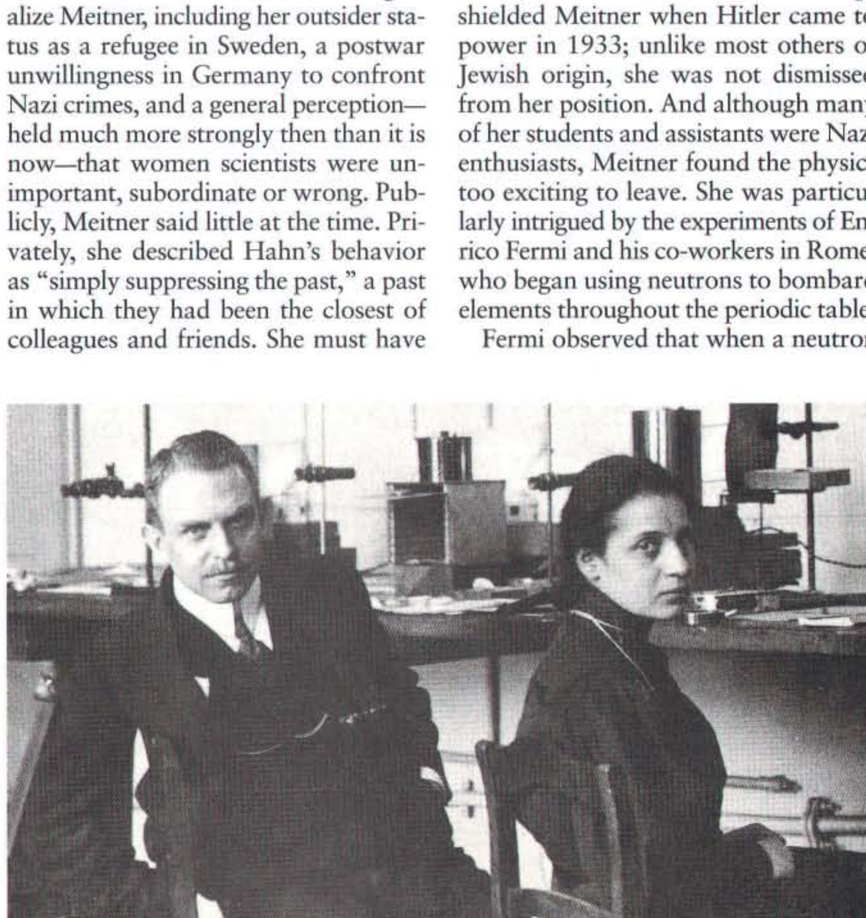
Born and educated in Vienna, Lise Meitner moved to Berlin in 1907 at the age of 28. There she teamed up with Otto Hahn, a chemist just her age, to study radioactivity, the process by which one nucleus is transformed into another by the emission of alpha or beta particles. Their collaboration was capped by their discovery in 1918 of protactinium, a particularly heavy radioactive element. As their careers progressed, they remained equals scientifically and professionally: both were professors at the Kaiser Wilhelm Institute for Chemistry, and each maintained an independent section in the institute—his for radiochemistry, hers for physics.

During the 1920s, Hahn continued developing radiochemical techniques, whereas Meitner entered the new field of nuclear physics. Hahn later described this period as a time when her work, more than his, brought international recognition to the institute. Her prominence, and her Austrian citizenship, shielded Meitner when Hitler came to power in 1933; unlike most others of Jewish origin, she was not dismissed from her position. And although many of her students and assistants were Nazi enthusiasts, Meitner found the physics too exciting to leave. She was particularly intrigued by the experiments of Enrico Fermi and his co-workers in Rome, who began using neutrons to bombard elements throughout the periodic table.

Fermi observed that when a neutron

LISE MEITNER (shown at left in about 1930, at the age of 50) was regarded as one of the leading nuclear physicists of her day. Although she smoked and worked with radioactivity all her adult life, she lived to the age of 90. Otto Hahn and Meitner (*right*), photographed in their laboratory at the University of Berlin around 1910, were colleagues and good friends from 1907 until Meitner was forced to flee from Germany in 1938.

PORTRAIT © ATELIER LOTTE MEITNER-GRAF, PHOTO COURTESY OF ARCHIV ZUR GESCHICHTE DER MAX-PLANCK-GESELLSCHAFT, BERLIN



COURTESY OF ARCHIV ZUR GESCHICHTE DER MAX-PLANCK-GESELLSCHAFT, BERLIN

COURTESY OF DEUTSCHES MUSEUM, MUNICH

MEITNER'S PHYSICAL APPARATUS was used by the Berlin team from 1934 to 1938 for work that resulted in the discovery of nuclear fission. Beginning in the 1950s, it was displayed in the Deutsches Museum for some 30 years as the "Worktable of Otto Hahn," with only a passing reference to Fritz Strassmann and no mention of Meitner.

reaction occurred, the targeted nucleus did not change dramatically: the incoming neutron would most often cause the target nucleus to emit a proton or an alpha particle, nothing more. Heavy elements, he found, favored neutron capture. That is, a heavy nucleus would gain an extra neutron; if radioactive, the heavier nucleus would invariably decay by emitting beta rays, which transformed it into the next higher element. When Fermi irradiated the heaviest known element, uranium, with neutrons, he observed several new beta emitters, none with the chemical properties of uranium or the elements near it. Thus, he cautiously suggested that he had synthesized new elements beyond uranium. All over the world, scientists were fascinated.

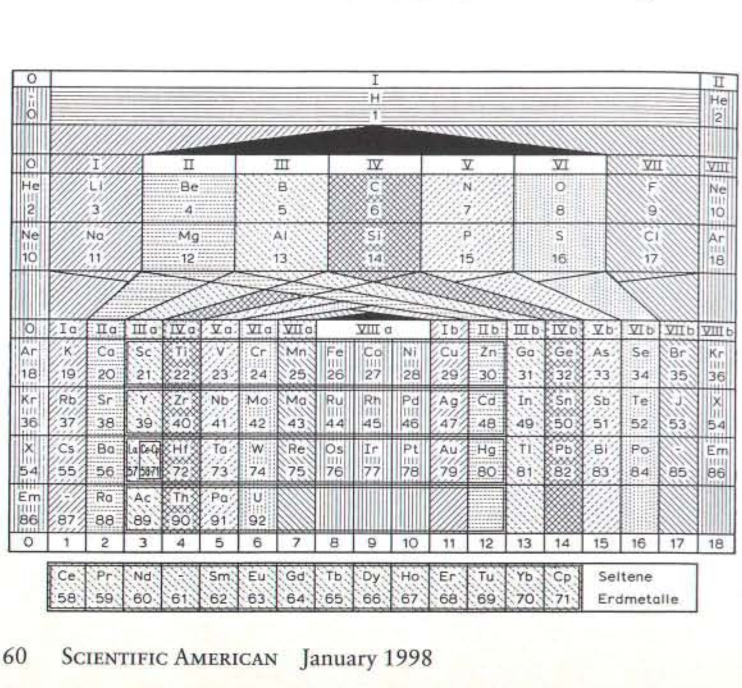
Meitner had been verifying Fermi's results up to this point. The work perfectly suited her interests and expertise, and she was then in her prime: one of the first women to enter the upper ranks of German science, she was a leading nuclear physicist of her day. To study these new "transuranics" in detail, however, Meitner needed an outstanding radiochemist. Hahn, though reluctant at first, agreed to help, and Fritz Strassmann, an analytical chemist from the institute, also joined the collaboration. The three were politically compatible: Meitner was "non-Aryan," Hahn was anti-Nazi, and Strassmann had refused to join the National Socialist–associated German Chemical Society, making him unemployable outside the institute.

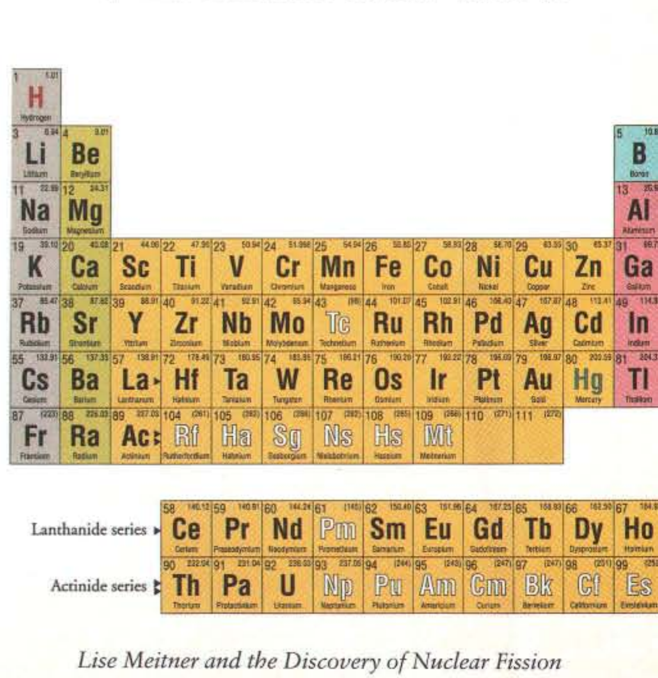
By the end of 1934, the team reported that the beta emitters Fermi observed could not be attributed to any other known element and that they behaved in a manner expected for transuranics: they could be separated out of the reaction mixture along with transition metals, such as platinum and rhenium sulfides. Thus, like Fermi, the Berlin scientists tentatively suggested that these activities were new elements beyond uranium. As it turned out, the interpretation was incorrect: it rested on two assumptions—one from physics and one from chemistry—that would prove false only several years later.

From physics, it had until then been observed that only small changes could take place during nuclear reactions, leaving an event such as fission unimaginable. And from chemistry it appeared that transuranic elements would be

PERIODIC TABLE of the 1920s and 1930s (*below left*) led researchers to expect that the elements following uranium would be transition elements. After the discovery of several transuranic elements in the 1940s, Glenn T. Seaborg recognized that the actinides form a second rare-earth series homologous to the lanthanides (*1995 periodic table, below right*). Element 109 was named meitnerium in 1994.

FROM *The Periodic System of Chemical Elements*, by J. W. Van Spronsen, Elsevier, Amsterdam, 1969 (*left*); COURTESY OF LAWRENCE BERKELEY NATIONAL LABORATORY, UNIVERSITY OF CALIFORNIA (*right*)





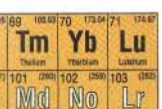
transition elements. It was a simple mistake: the chemistry of thorium and uranium is quite similar to that of transition elements, so chemists in the 1930s also expected that the elements beyond uranium would be transitionlike, resembling rhenium, osmium, iridium and platinum.

Untangling Decay Chains

The two false assumptions reinforced each other, misleading the investigation for several years. Later Hahn blamed physicists and their mistaken faith in small nuclear changes for obstructing the discovery. If anything, however, the scientific publications indicate that the chemists were complacent and the physicists were more skeptical. Physics did not predict fission, to be sure, but it detected discrepancies that chemistry could not.

The Berlin scientists had tried to separate the presumed transuranics, which had extremely weak activities, from uranium and its decay products, which had much stronger, natural radioactivity. After irradiating a uranium sample with neutrons, they would dissolve the sample and then separate from the solution just those activities with the chemistry of transition metals, generally by using transition-metal compounds as carriers. The precipitate itself was a mixture of several beta emitters, which the Berlin team painstakingly began to disentangle.

Over two years, they identified two parallel beta-decay chains, which they referred to as processes one and two [*see box at right*]. The sequence of these decays corresponded to the properties expected for the elements following uranium: they resembled the transition elements rhenium, osmium and so on. The fit between the sequences and the predicted chemistry seemed too good not to be true. Publishing in *Chemische Berichte* in 1936 and 1937, with Hahn as the senior author, the elated group repeatedly referred to these transuranics as "unquestionable," there being "no doubt" about their existence and "no need for further discussion."



All the while, the data were stretching physical theories thin. Meitner struggled to integrate the results from chemistry, radiochemistry and her own physical measurements into a cogent model of the nuclear processes involved. She established that thermal—exceedingly slow—neutrons enhanced the yield of processes one and two, evidence that these events involved neutron capture. But fast neutrons generated the same results. Thus, she concluded that both processes originated with the most abundant uranium isotope, uranium 238. She also identified a third process—involving the capture of moderately slow neutrons—for which there was no long beta chain.

Meitner regarded it as odd that three different neutron-capture processes all originated from the same uranium 238 isotope. She suspected that something was very wrong with processes one and two. From theoretical considerations, she could not understand how the capture of a single neutron could produce such great instability that it would take four or five beta emissions to relieve it. And it was even harder to understand that the two long beta-decay chains paralleled each other for several steps. Theory offered no explanation. In a 1937 report to *Zeitschrift für Physik*, Meitner concluded that the results were

Discovering Fission

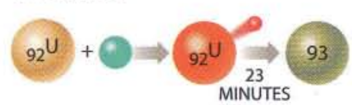
The Berlin group found that a large number of beta emitters (radioactive nuclei that emit electrons) were formed when neutrons hit uranium nuclei. The researchers proposed two chains, which they believed consisted of elements beyond uranium, each with its own rate of beta decay:

Process 1

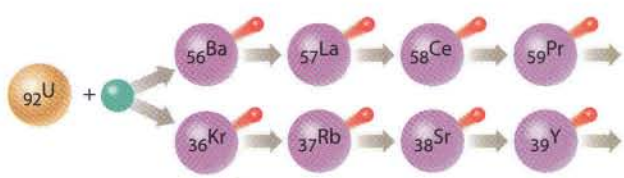
Process 2

In addition, they identified a simpler reaction:

Process 3



Meitner regarded process three as the most understandable, and later it was shown to be correct. But she was puzzled by processes one and two because the decay chains were so long and paralleled each other. Ultimately, when Hahn and Strassmann identified one of the reaction products as barium, Meitner and Frisch realized that the uranium nucleus had split into nuclei of barium and krypton, which began a series of beta emissions:



JARED SCHNEIDMAN DESIGN

These nuclei and other fission fragments account for the decay chains of processes one and two. Meitner and Frisch proposed the name "nuclear fission," published the first theoretical explanation of the process and predicted the enormous energy released. —*R.L.S.*

COURTESY OF ARCHIV ZUR GESCHICHTE DER MAX-PLANCK-GESELLSCHAFT, BERLIN

IN THE 1920s Meitner, as professor and head of her own section for physics at the Kaiser Wilhelm Institute for Chemistry, became prominent in nuclear physics. In this photograph, taken in 1920 when Niels Bohr first visited Berlin, are some of her closest colleagues and friends; nearly half would win Nobel Prizes. *Front row:* Otto Stern (Nobel, 1943), James Franck (1925), Bohr (1922). *Second from right:* Gustav Hertz (1925). *To Meitner's right and back:* Hahn (1944) and George de Hevesy (1943).

"difficult to reconcile with current concepts of nuclear structure."

Once fission was recognized, researchers understood that processes one and two were fission processes: the uranium splits into fragments that are highly radioactive and form a long sequence of beta decays. (There can be many such decay chains because uranium can split in many ways.) Meitner regarded process three as the most normal, and later this was shown to be correct: the uranium 239 isotope formed in this neutron-capture reaction decays by beta emission to element 93. In 1940 it was identified by Edwin McMillan and Philip Abelson and later named neptunium. Had the Berlin scientists been able to detect neptunium, they would have found that it is a rare-earth element, and they would have realized that the activities in processes one and two are not transuranics. But they did not detect it; their neutron sources were too weak.

AIP EMILIO SEGRÈ VISUAL ARCHIVES, *PHYSICS TODAY* COLLECTION

OTTO R. FRISCH and Meitner were the first to explain, in 1939, the fission process. In England in 1940 he and fellow émigré Rudolf Peierls analyzed the potential of nuclear fission for use in weapons and helped to launch the Allied atomic bomb project.

Identifying Barium

The most serious error the Berlin team made was that the investigators separated out and studied only those activities with transition-metal chemistry, ignoring all others. In 1938 in Paris, Irène Curie and Pavel Savitch used a different technique to examine the entire mixture of uranium products and found a new, strong activity whose chemistry they could not ascertain. Like the presumed transuranics, its yield was enhanced by thermal neutrons. By the time the Berlin team looked into it in October 1938, however, Meitner had been forced to flee Germany for Stockholm. Hahn and Strassmann analyzed the Curie activity alone and, finding that it followed a barium carrier, identified it as an isotope of radium.

Meitner and Hahn corresponded constantly, and mail between Stockholm and Berlin was delivered overnight. She could scarcely believe the radium result. To form radium, the uranium nucleus would have to emit two alpha particles. Meitner was convinced that it was energetically impossible for a thermal neutron to knock out even one alpha particle—and certainly not two. In November 1938 Meitner visited Niels Bohr's Institute for Theoretical Physics in Copenhagen, and Hahn met her there on November 13. Outside the city their meeting was kept secret to avoid political difficulties for Hahn, and he never mentioned it later in his memoirs. But we know from Hahn's own pocket diary that they met, and we know that Meitner objected strenuously to the radium result. That was the message Hahn brought back to Strassmann in Berlin.

According to Strassmann, Hahn told him that Meitner "urgently pleaded" that they verify the radium one more time. "Fortunately, her opinion and judgment carried so much weight with us that we immediately began the necessary control experiments," Strassmann remembered. With these experiments, they intended to verify the presence of radium by partially separating it from its barium carrier. But no separation occurred, and they were forced to conclude that their "radium" was in fact an isotope of barium, an element much lighter than uranium.

In December 1938, just before Christmas, Hahn told Meitner about the barium. It was a "frightful result," he wrote. "We know uranium cannot really break up into barium!" He hoped she could propose "some fantastic explanation." Meitner answered by return mail. Although she found it difficult to think of a "thorough-going breakup," she assured him that "one cannot unconditionally say: it is impossible." Her letter must have been the best Christmas present he ever received. She had vehemently objected to the radium result, but she was ready to consider the barium result as expanding, rather than contradicting, existing theory.

Later, Hahn was known to say that if Meitner had still been in Berlin, she might have talked him out of the barium result and might have "forbidden" him from making the discovery. But Meitner's letter, which Hahn always had in his possession, demonstrates that the

opposite is true. And at the time, Hahn clearly found her letter reassuring, because only after he received it did he add a paragraph to the galley proofs of his barium publication, suggesting that the uranium nucleus had split in two. Meitner was bitterly disappointed that she could not share in this "beautiful discovery," as she called it, but they all knew that it was impossible to include a "non-Aryan" in the publication.

Revising Nuclear Theory

For Christmas, Meitner visited a friend in western Sweden, and her nephew, Otto Frisch, a physicist at Bohr's institute, joined her. When Meitner and Frisch came together, so, too, did the various strands of nuclear theory. Both were accustomed to thinking of the nucleus as a liquid drop, but now they visualized it as a wobbly, oscillating drop that was ready to split in two. Frisch realized that the surface tension of a nucleus as large as uranium might be vanishingly small. Meitner did the mass defect calculation in her head and estimated the lost mass that was converted to enormous energy when the nucleus split. Everything fell into place: the theoretical interpretation itself was a beautiful discovery—and it was recognized as such. The physics community immediately adopted the term "fission" that Meitner and Frisch proposed, and Bohr used their work as a starting point for a more extensive theory.

Hahn and Strassmann's barium finding appeared in *Naturwissenschaften* in January 1939; Meitner and Frisch published their interpretation in *Nature* a few weeks later. On the surface, the discovery of fission was now completely divided—chemistry from physics, experiment from theory, Germans from refugees. To those who did not understand the science or who did not care to understand the politics, it might appear that chemists had discovered fission, whereas physicists had only interpreted it.

In the weeks following the discovery, Hahn exploited that artificial division. He knew Meitner's forced emigration was unjust. He knew she had fully participated in the discovery. But he could not say so. He was afraid for himself and for his position and terribly afraid that others would find out that he and Strassmann had continued to collaborate with Meitner after she left Berlin. He decided that the discovery of fission consisted of just those chemical experiments that he and Strassmann had done in December. In February 1939 he wrote to Meitner, "We absolutely never touched on physics, but instead we did chemical separations over and over again." He described fission as a "gift from heaven," a miracle that would protect him and his institute.

As it turned out, it may not have been necessary for Hahn to divorce himself from Meitner and physics to make the "miracle" come true. That spring the German military took an active interest in the potential uses of the new discovery, and by the summer of 1939 Hahn and his institute were secure. Later he recalled that "fission saved that whole situation."

After the atomic bomb, fission was more sensational than ever, and Hahn was a very famous man. In postwar Germany, he was a major public figure for a generation, lionized as a Nobel laureate and a decent German who never gave in to the Nazis, a scientist who did not build a bomb. His treatment of Meitner, however, was anything but decent. Not once in his numerous articles, interviews, memoirs or autobiographies did he mention her initiative for the uranium project, her leadership of their team in Berlin or their collaboration after she left. He died in Göttingen in 1968 at the age of 89.

In Sweden during the war, Meitner's professional status was poor. Her friends believed that she almost surely would have been awarded a Nobel Prize had she emigrated anywhere else. In 1943 she was invited to Los Alamos to work on the atomic bomb, but she refused. For a brief period after the war ended, she was a celebrity in the U.S. and Britain, miscast as the Jewish refugee who escaped the Nazis with the secret of the bomb. But Meitner was a private person who detested publicity. She never wrote an autobiography or authorized a biography. She left Stockholm for Cambridge, England, in 1960 and died there in 1968, a few days before her 90th birthday. Sadly, she died some 30 years before she received proper recognition for her work.

COURTESY OF IRMGARD STRASSMANN

FRITZ STRASSMANN worked with Meitner and Hahn on the investigations that led to the discovery of nuclear fission. His knowledge of analytical chemistry was crucial to the identification of barium. A courageous anti-Nazi, he helped to save the life of a Jewish friend during the war.

The Author

RUTH LEWIN SIME was born in New York City in 1939. She received a bachelor's degree in mathematics from Barnard College in 1960 and obtained a doctorate in chemistry from Harvard University in 1964. Since 1968, she has taught chemistry at Sacramento City College. Her interest in Lise Meitner began some 25 years ago, when she taught a class on women in science and discovered that little scholarly attention had been paid to Meitner's life and work. Her biography *Lise Meitner: A Life in Physics* was published in 1996 by the University of California Press.

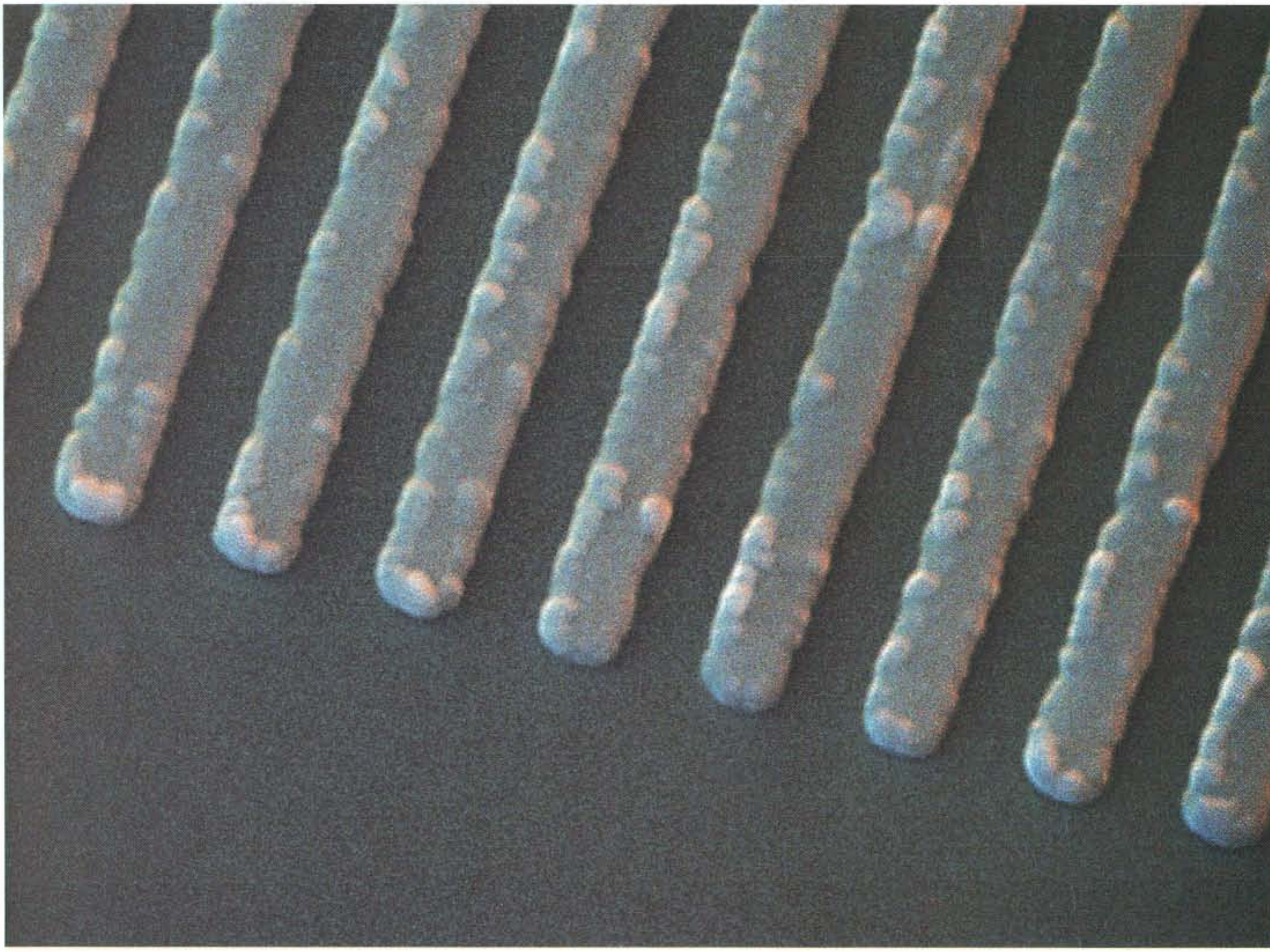
Further Reading

LOOKING BACK. Lise Meitner in *Bulletin of the Atomic Scientists*, Vol. 20, pages 1–7; November 1964.

WHAT LITTLE I REMEMBER. Otto R. Frisch. Cambridge University Press, 1979.

IM SCHATTEN DER SENSATION: LEBEN UND WIRKEN VON FRITZ STRASSMANN. Fritz Krafft. Verlag Chemie, Weinheim, 1981.

A NOBEL TALE OF POSTWAR INJUSTICE. Elisabeth Crawford, Ruth Lewin Sime and Mark Walker in *Physics Today*, Vol. 50, No. 9, pages 26–32; September 1997.



DAVID SCHARF

Picosecond Ultrasonics

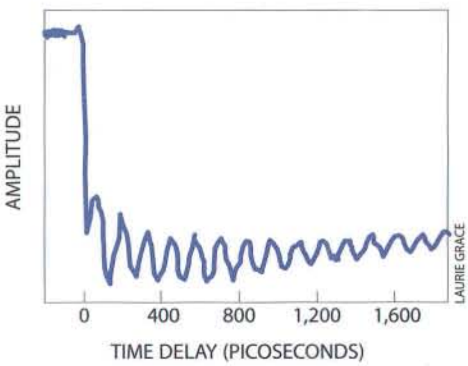
Brief pulses of high-frequency sound allow experimenters to probe connections inside a computer chip

by Humphrey Maris

During the past three decades, humans have developed a remarkable ability to manufacture small objects. A prime example is the computer chip, made from a silicon wafer with strategically placed impurities that form transistors. On top of each chip is a sequence of metal films and insulating layers that electrically connect the transistors to their neighbors. The films may be as thin as a millionth of a centimeter. Their thickness and uniformity determine the efficiency of the chip and, ultimately, the computer it is in.

A film may be anywhere from 50 angstroms to a few microns thick (one angstrom equals 10^{-8} centimeter, whereas one micron equals 10^{-4} centimeter). For the finest films, the thickness has to be controlled to an accuracy of one angstrom—less than the size of an atom. Measuring the thickness is exceedingly difficult. The most efficient means currently available is destructive: take a chip, cut it and look at it from the side. Most manufacturers deal with the problem of ensuring consistent thickness by minutely controlling every aspect of the production process—such as temperature, humidity and pressure—and by checking the dimensions of the few chips that are sacrificed.

In 1985, while conducting optical experiments on a semiconductor, my colleagues and I at Brown University happened to direct a short pulse of light at a metal film on the sample's surface. Our objective was to study the response



NANOXYLOPHONE (*opposite page*), an instrument that makes sound at a frequency of eight billion hertz (or 24 octaves above middle C), is made of gold bars, each less than 150 atoms thick. The chart (*left*) shows the time profile of the emitted sound. Waves of even smaller frequencies, some lasting only a picosecond (10^{-12} second), are helping to probe the configurations inside computer chips.

of the electrons within. On sending in a second light pulse, however, we noticed that the reflectivity of the surface was changing in a periodic fashion. Amazingly, the film was vibrating, emitting sound waves with minute wavelengths of about 500 angstroms. Until that time, no one had surmised that sound pulses of such high frequency and, as it turned out, brief duration could be created.

Since then, we have been developing a technique to use these extraordinarily short sound pulses to measure small structures such as the metal skins on a chip. By listening for the separate echoes returning from top and bottom surfaces, we can determine a film's thickness.

Nature's Technology

To consider what is required for using sound to measure thickness, recall one of nature's technological miracles, the bat. In 1912 Hiram Maxim, an expatriate American better known for building aircraft and inventing the machine gun, suggested that bats use sonar—sound navigation and ranging—to determine the location of flying insects. To humans, bats often seem mute, so Maxim proposed that bats use the sound generated by the flapping of their wings. But such low-frequency sound consists of long waves that flow around small objects without being readily scattered. So, on the basis of Maxim's theory, it was hard to understand how the bat could hear the very small echo from a flying insect.

In 1920 Hamilton Hartridge of the University of Cambridge proposed that a bat emits pulses of ultrasound—having frequencies above the audible range for humans—and detects insects by means of their echoes. George W. Pierce and Donald R. Griffin of Harvard University first observed these pulses in 1938. Since then, observers have learned that dolphins, as well as some birds, employ sonar. Even the humble whirligig beetle uses the reflection of the bow wave produced as it moves through water to locate objects.

Bat sonar is surprisingly sophisticated. Because the insect is in motion, the echo from it will have a slightly different frequency from the sonic pulse sent out by the bat. This frequency shift, called the Doppler effect, allows the bat to estimate the speed and direction of the insect. (Highway police similarly rely on the Doppler effect to snare motorists in speed traps.) In addition, within each pulse it emits, the bat varies the frequency of the sound. This modulation, called chirping, aids the bat in analyzing the echo and probably helps it distinguish other attributes of its prey, such as shape, size, the rate at which it beats its wings, and even whether it is a beetle or a moth.

To determine the distance to an insect, the bat has to send a short pulse of sound, so that it has finished emitting before the echo returns. The speed of sound in air is 330 meters per second. So if an insect is at a distance of 3.3 meters, sound takes just a fiftieth of a second to travel to the insect and back. As the bat homes in on an insect, it emits fast, staccato bursts of brief chirps, as short as a millisecond each, to locate insects to within a meter.

For gauging the thickness of very small metal structures, the time problem becomes even more severe. The speed of sound in aluminum is 6,000 meters per second, about 20 times greater than in air. So a round-trip through an aluminum film a millionth of a centimeter thick takes a sound wave about three trillionths of a second. Consequently, to perform sonar measurements on such small objects, my colleagues and I had to find a way to generate even briefer pulses, lasting a trillionth of a second or less.

To generate sound in a solid or a liquid, laboratory workers generally use a piezoelectric transducer. This device is made of a material such as quartz, which expands slightly when a voltage is applied to it. So when subjected to an alternating voltage, the transducer vibrates, launching a compression wave—a sound pulse—of the same frequency. With this technique, dating from the 1920s, experimenters can produce sound with frequencies ranging from 100 kilocycles to 1,000 megacycles and lasting for as little as a millionth of a second. Such brevity allows thickness measurements of down to a few millimeters. That resolution, unfortunately, is not adequate to deal with computer chips.

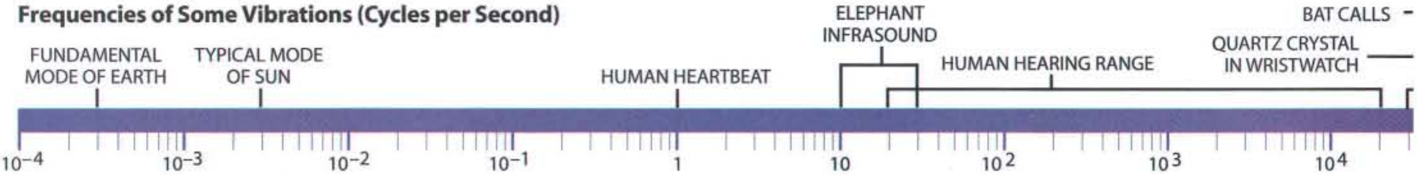
Like many developments in science, progress in this field eventually arose from advances, over many years, in a seemingly unrelated area of research. In 1960 Theodore Maiman of Hughes Research Laboratories in Malibu, Calif., constructed the first laser. He used a flash lamp to excite chromium atoms in a ruby rod to states of higher energy. The excess energy of these atoms could then be employed to amplify light trapped inside the rod.

This laser produced intense pulses of red light lasting less than a thousandth of a second. In the following years many other types of lasers came into being, including gas, dye, chemical and solid-state devices based on a variety of materials and mechanisms. (One laser even uses gelatin as its active material—and can be eaten after use!) By the early 1980s lasers could produce a stream of light pulses as short as 10^{-14} second. A light packet this short amounts to a ripple in the electromagnetic field containing only five wavelengths and extending over three microns.

In our laboratory we use light from a pulsed laser to make sound. The laser is focused onto the surface of a material, which absorbs the photons into a very thin layer at the top. The energy of the photons is initially taken up by electrons, which quickly move a small distance into the material, losing energy as they travel. As a result, the temperature of the material near the surface suddenly increases by a few degrees, causing the layer to expand. A sound wave—sometimes a single, isolated compression, sometimes a train of these—then launches into the material.

The pulse of sound produced in this way can be as brief as a picosecond (10^{-12} second), and its length in space can be just a few nanometers. Its amplitude, or the distance it causes atoms to move, is about a trillionth of a centimeter, or roughly 10 times the diameter of an atom's nucleus.

After finding a way to generate sound, we still need a way to detect these tiny pulses after they have traveled through



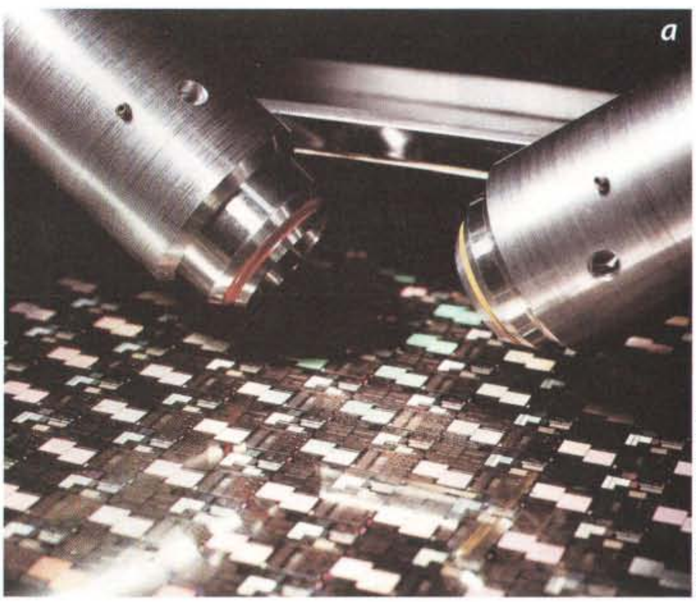
the sample under study. As it happens, we know how to do this from the serendipitous discovery mentioned earlier. When the echo returns to the surface, it periodically compresses the material, causing a change in its ability to reflect light. This change can be detected by a second light pulse directed at the surface.

The ultrasound pulses can measure the thickness of a film with an accuracy of less than an angstrom—far shorter than the wavelength of the sound, which ranges from 50 to 500 angstroms. Common wisdom among physicists holds that this is not possible: a wave cannot provide a resolution finer than its own wavelength. In practice, we violate this rule by comparing the profile of the emitted sound wave with that of the returned wave. Even if the ends of a wave are poorly defined, the position of its peak can be located very precisely. So we can determine the time at which the echo peaks to within a fraction of a picosecond, thus getting the distance it has traveled to within an angstrom. The measurement is analogous to interferometry, a technique for comparing the forms of two waves.

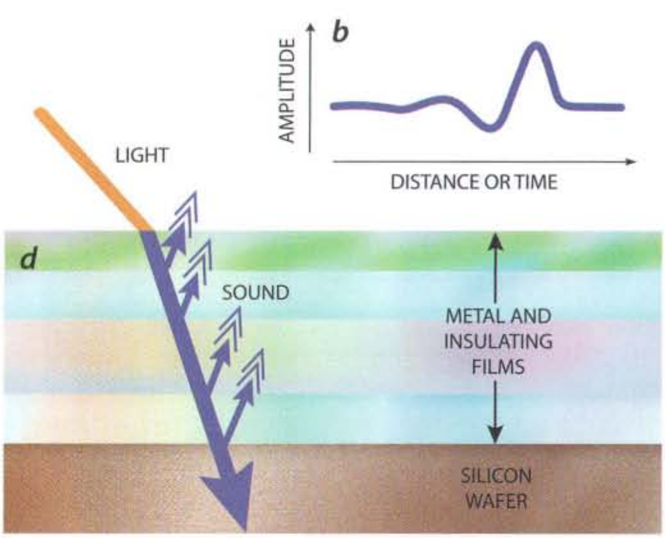
Having gotten to this point, some of us had another, less relevant idea: if we can make sound, surely we can also make music. Aided by experts from the IBM Thomas J. Watson Research Center in Yorktown Heights, N.Y., we made a "nanoxylophone." The instrument looks like any other xylophone except that each bar is a slab of gold less than 400 angstroms—that is, 150 atoms—thick

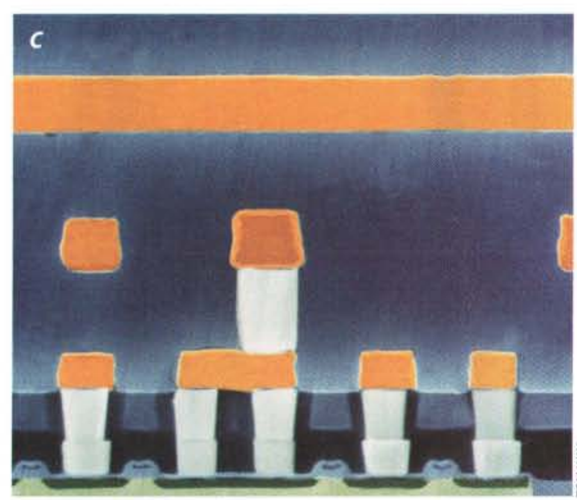
Picosecond Probe

Properties of the metal layers inside a silicon chip are probed by ultrasound. A laser (*a*) directed at the chip's surface heats the chip and generates a pulse of sound (*b*), about 100 angstroms or a picosecond long. The sound is reflected by various structures within the chip, seen in cross section (*c*) and idealized in the diagram (*d*). When it returns to the surface, the echo changes its optical properties, which are measured by a second laser. The echo is then matched with a computer model (*e*) to determine the exact location, thickness and bonding of the internal layers. —*H.M.*

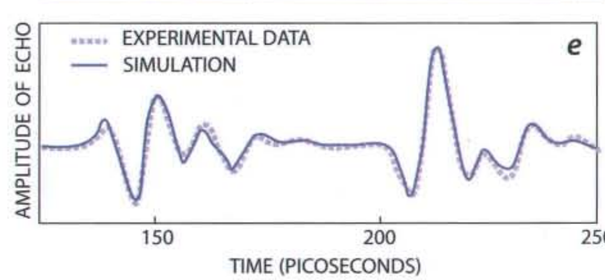


COURTESY OF HUMPHREY MARIS

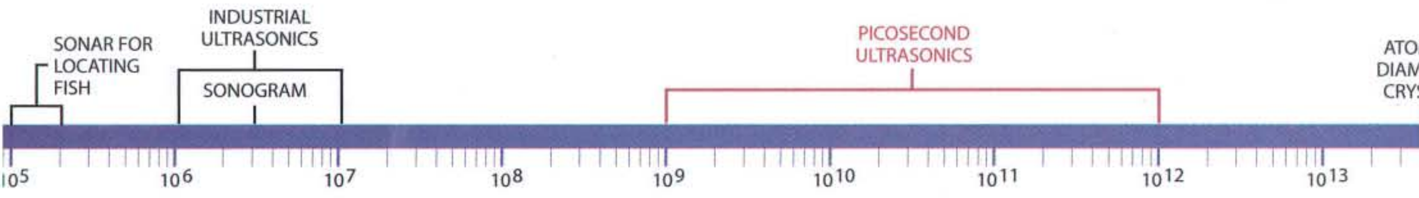




TOM WAY



LAURIE GRACE (*graphs*)



and 2,000 angstroms wide. When we strike the nanoxylophone with a light pulse, it produces a note of eight billion vibrations per second, about 24 octaves above middle C. We have since made other small structures that vibrate when excited by a light pulse; the highest pitch attained is 700 billion vibrations per second, or about 31 octaves above middle C. (Regrettably, the nanoxylophone is quite useless for music: all its bars produce pretty much the same note.)

These techniques have practical implications in testing computer chips. The fabrication of a chip is an intricate process of several hundred steps, taking many weeks to complete. It starts with a crystal of very pure silicon, sliced and polished into round wafers, usually 20 centimeters in diameter and a fraction of a millimeter thick. Into parts of the chip's surface are implanted specially selected impurities, to form the transistors that determine the chip's characteristics. On top of the wafer, technicians deposit a sequence of thin films made of different materials, some metallic and some insulating. This sequence forms a "stack."

The metal films serve as electrical connections between different parts of a chip; they form a complex pattern running across the wafer, rather like a freeway system with overpasses and junctions. Insulating films, usually of glass or polymer, electrically isolate the different layers of metal. The entire fabrication process requires extreme cleanliness and control; a single dust particle can ruin a chip. In the end, each wafer is divided to form roughly 100 chips.

Any unnoticed change in the fabrication process can lead to disastrous results. In particular, the operation of a chip requires that the actions of all its constituent transistors be synchronized. So the time taken by a signal to pass from one transistor to another is critically important. This "time constant" is proportional to the resistance of the metal film separating the two components; the resistance, in turn, is inversely proportional to the film's thickness. So controlling the thickness is vital to the functioning of a chip.

A Chip and Beyond

Picosecond ultrasonics can allow manufacturers to measure the thickness of the different thin films in a chip accurately. First a light pulse, focused onto the part of the film that is to be studied, is absorbed in the uppermost layer of the stack. The heating and the resulting expansion generate a sound pulse that travels through the stack. Each time the sound reaches the boundary between two films, a part of it is reflected back. From the time taken by these echoes to return to the top of the stack, researchers can accurately calculate the thickness of each layer.

This method is similar to the seismological techniques used by geologists to determine the thickness of different layers of the earth's crust. There is a difference, however: the films in the stacks are thin enough that sometimes the sound waves return on one another's heels and can overlap. When light reflects from a film of oil on water, similar "interference" leads to colorful patterns (occasionally visible in parking lots). In our case, the interfering waves generate a pattern of beats that we have to decipher to learn the geometry and dimensions of the films.

The echoes can betray many other characteristics of the film stack. When a sound pulse reflects from a rough boundary, for instance, it will broaden in space and time. Therefore, analyzing the echo's shape can indicate the roughness of a surface. In addition, from the echo's loudness, it is possible to tell how well a pair of adjacent films are bonded. If the films are loosely connected, perhaps because of some contamination, sound cannot cross the boundary, and so most of the pulse will be reflected. Thus, the strength of the echoes from the different interfaces allows us to verify that the films are strongly bonded and that the chip is unlikely to fail mechanically.

In the next stage of our research, we hope to employ picosecond ultrasonics in studying processes that occur within biological cells. Ultrasound is already extensively used to observe the development of a baby inside the womb. With the new techniques for producing very short pulses, we may be able to perform analogous experiments inside a living cell. We hope sound waves can help create an acoustic image of the cell, enabling researchers to monitor its development. For example, with picosecond ultrasonics it may be possible to obtain an image of the cytoskeleton—the cell's supporting framework—with detail comparable to that of conventional x-ray images of a human skeleton.

Although nature far outpaces humans in the manufacture of small objects, and perhaps always will, the gap continues to narrow. Picosecond sound bursts allow a way to follow the race. SA

The Author

HUMPHREY MARIS has been a professor of physics at Brown University since 1965. He obtained his Ph.D. from Imperial College, London. His current research includes developing a detector for solar neutrinos, magnetic and laser levitation using superfluid helium, experiments on liquids at negative pressures, as well as picosecond ultrasonics.

Further Reading

NONINVASIVE PICOSECOND ULTRASONIC DETECTION OF ULTRATHIN INTERFACIAL LAYERS: CF_x AT THE AL-SI INTERFACE. G. Tas et al. in *Applied Physics Letters,* Vol. 61, No. 15, pages 1787–1789; October 12, 1992.

STUDY OF VIBRATIONAL MODES OF GOLD NANOSTRUCTURES BY PICOSECOND ULTRASONICS. H.-N. Lin et al. in *Journal of Applied Physics,* Vol. 73, No. 6, pages 37–45; January 1, 1993.

THE SCIENCE AND ENGINEERING OF MICROELECTRONIC FABRICATION. Stephen A. Campbell. Oxford University Press, 1996.

ULTRASONIC MULTILAYER METAL FILM METROLOGY. C. J. Morath et al. in *Solid State Technology,* Vol. 40, No. 6, pages 85–92; June 1997.

The Placebo Effect

Colds, asthma, high blood pressure and heart disease are among the many conditions that can respond to treatment with a placebo.

Should doctors be prescribing sugar pills?

by Walter A. Brown

After a day of cross-country skiing in subfreezing weather a couple of years ago, I developed severe lower back pain. Even tying my shoes was agony. Despite my suffering, I knew there was no serious underlying disease, so I was certain I would be back to normal in no time.

But the days wore on with no change. A heating pad and suggestions from a friend with a chronic back problem (lie down, tuck your chin when you bend over) didn't help. After a week, I became desperate. I called my cousin Gary, who is a physical therapist. When I have consulted him in the past about sprains and tendonitis, his advice has always been on target. I was confident I was in the hands of an expert.

As usual, Gary was upbeat and authoritative. After taking my history and putting me through some maneuvers, he identified the muscles involved. He told me to ice the area, prescribed a set of exercises to stretch the constricted muscles and suggested that I take ibuprofen. When the consultation was over, I still had the back pain, but I had a technique for relieving it and the conviction that it would improve. Although my back was not yet better, I was.

I avoided the ibuprofen (it upsets my stomach), but I applied ice and exercised faithfully. Every time I did these things I felt a real sense of satisfaction. I was finally taking charge. Within two days the back pain had been reduced to a twinge; in a week it was gone.

I don't know whether the ice and exercise actually healed my inflamed, constricted muscles or whether they would have healed on their own in the same time. I do know that just seeking and receiving treatment made me feel better—less disabled, less distressed, more hopeful—and this in turn may have speeded my recovery. These benefits are called, often derisively, the placebo effect.

Powerful Healing

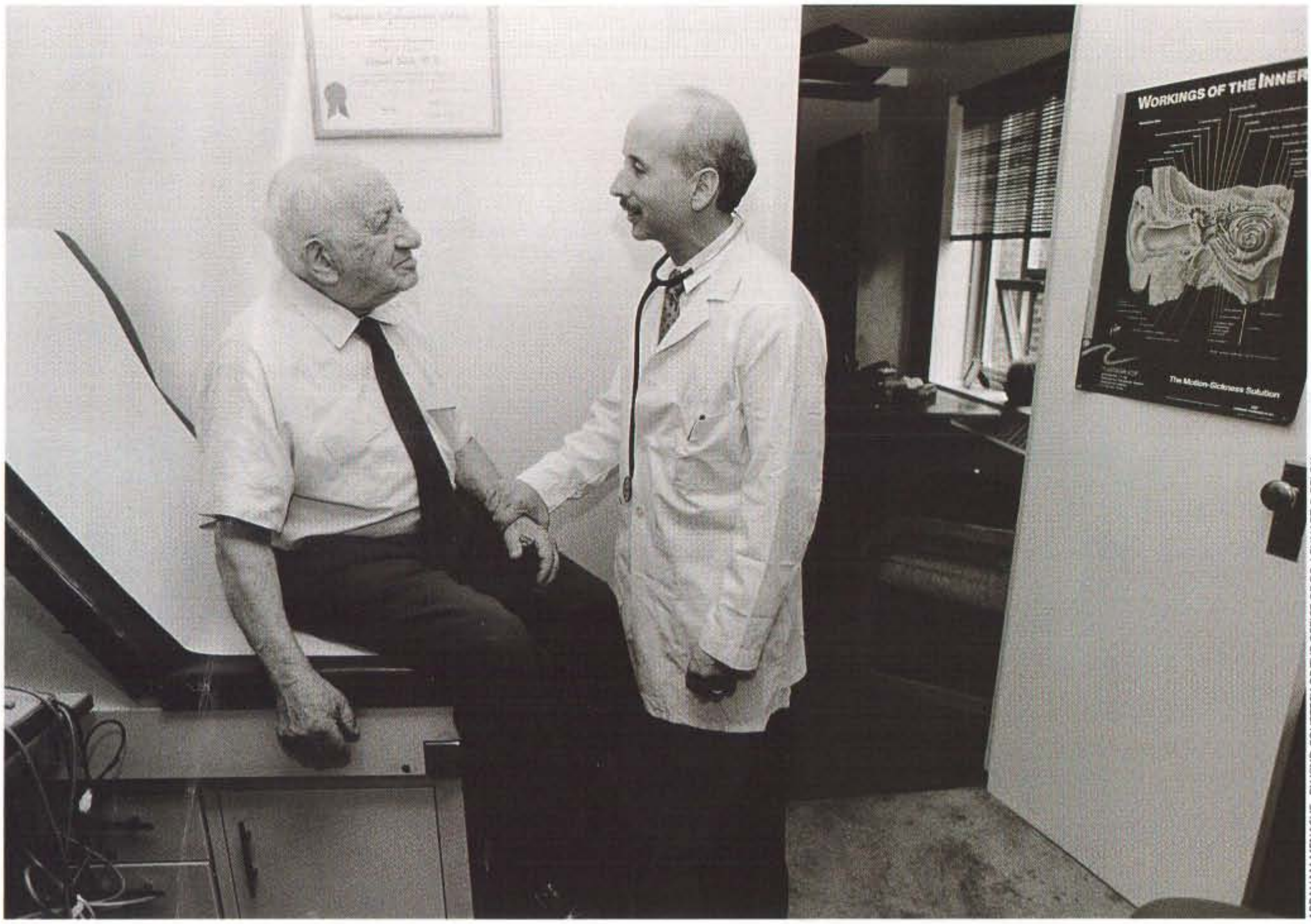
Medicine has become vastly more scientific in the past century—gone are the potions, brews and bloodlettings of antiquity. Nevertheless, doctors and their patients continue to ascribe healing powers to pills and procedures that have no intrinsic therapeutic value for the condition being treated (think of the widespread—and medically pointless—use of antibiotics to fight colds and flus caused by viruses). Some studies, including one by the U.S. Office of Technology Assessment, suggest that only about 20 percent of modern medical remedies in common use have been scientifically proved to be effective; the rest have not been subjected to empirical trials of whether or not they work and, if so, how. It is not that these treatments do not offer benefits: most of them do. But in some cases, the benefit may come from the placebo effect, in which the very act of undergoing treatment—seeing a medical expert, for instance, or taking a pill—helps the patient to recover.

Since the early 1980s, I have been investigating the placebo effect. In the course of my research, I have learned something about how placebos work, why they are disparaged by both patients and physicians, and who is most likely to benefit from them.

My information on these matters is far from complete. But based on what is known, I believe that the placebo effect is a powerful part of healing and that more effort should be made to harness and enhance it.

My interest in the placebo effect began when my colleagues and I found something unexpected while investigating the biochemistry of depression. In 1984 we were testing patients for the hormone cortisol, which is produced by the adrenal gland. In previous work, we and others had found that about half the patients with severe clinical depression produced excessive amounts of the hormone. We thought this group of patients might do better taking antidepressants than depressed patients with normal levels of cortisol would. (We speculated that patients with a biochemical imbalance might respond better to a biochemical treatment.)

To test this idea, we recorded levels of cortisol in patients who were about to enter a study of a new antidepressant medication. Mihály Arató, a young Hungarian psychiatrist working in my



ABRAHAM MENASHE; BY KIND COURTESY OF THE OFFICE OF DR. LENNART C. BELOK

The healing environment is a powerful antidote for illness.

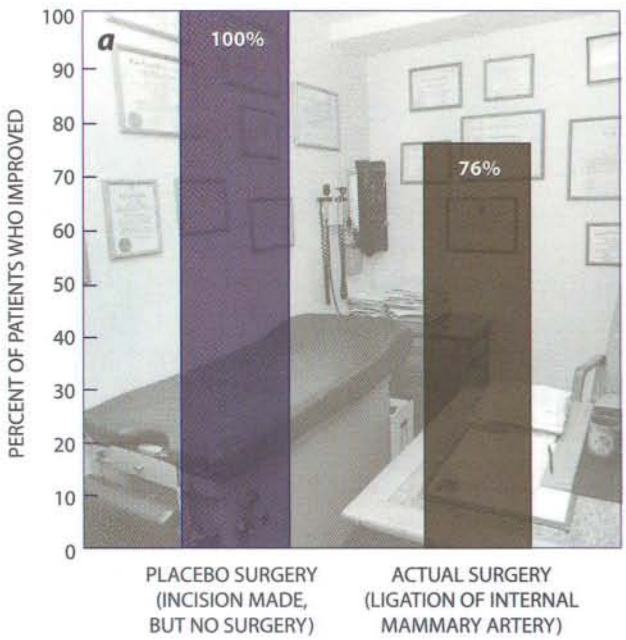
The decision to seek medical assistance restores some sense of control. The symbols and rituals of healing—the doctor's office, the stethoscope, the physical examination—offer reassurance.

laboratory at the time, took on the job of analyzing the results. At first glance, the conclusions were disappointing. Contrary to our hypothesis, depressed patients responded equally well to the drug, regardless of how much hormone was present in their system. And yet they did show one fascinating difference.

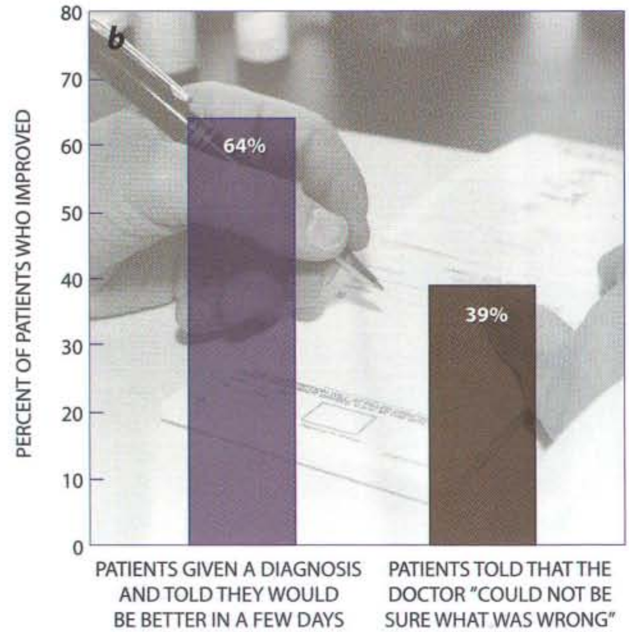
This research was part of a so-called double-blind study: some patients were treated with a placebo, and neither the doctors nor the patients knew who received the placebo and who received the antidepressant. When Arató examined the results from the placebo group, the outcome was striking. Typically 30 to 40 percent of depressed patients benefit from taking a placebo. In this case, close to half the 22 patients with normal levels of cortisol felt better after taking a placebo, but among the nine patients with elevated levels, none improved.

These findings, which have been confirmed in our lab and by other researchers, indicate that depressed patients who respond to placebos differ biochemically from those who do not. I wondered if they differed in other ways as well. As it turns out, they do. People suffering from short-term depression, lasting less than three months, for instance, are more likely to benefit from a placebo. But longer-term depression, lasting more

ANGINA PECTORIS: BENEFITS OF PLACEBO VS. SURGERY



GENERIC SYMPTOMS: BENEFITS OF DIAGNOSIS ALONE



than a year or so, often does not improve after placebo treatment.

Relieving Stress

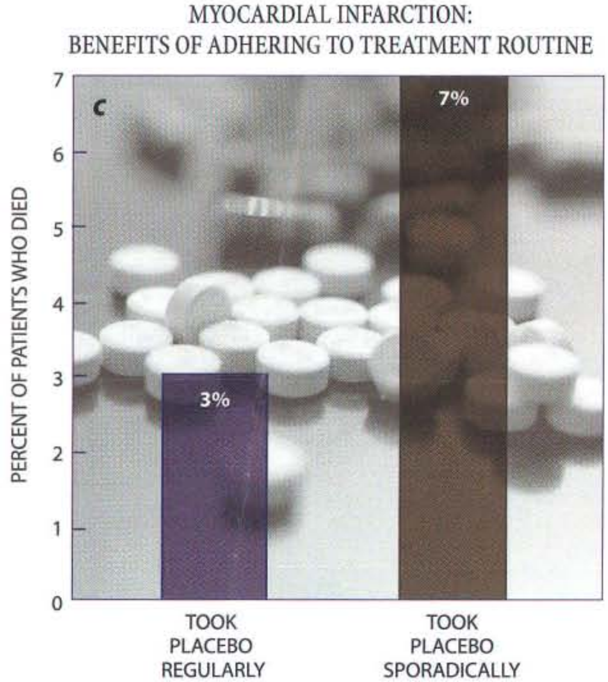
The placebo effect is not unique to depression or psychiatric illness. A landmark study in the early 1950s by Henry K. Beecher of Harvard University suggested that for a wide range of afflictions, including pain, high blood pressure, asthma and cough, roughly 30 to 40 percent of patients experience relief after taking a placebo. In some cases, the response can be even more pronounced: researchers led by Edmunds G. Dimond of the University of Kansas Medical Center in the late 1950s investigated the effectiveness of the then routine arterial ligation surgery to treat angina pectoris (chest pain caused by insufficient blood supply to the heart). The doctors performed the surgical procedure in one set of 13 patients; with a second group of five patients, they made only a chest incision but did no further surgery. Among the patients who received the actual surgery, 76 percent improved. Notably, 100 percent of the placebo group got better. (Arterial ligation surgery is no longer performed.)

So what exactly is this placebo treatment that compares so favorably with conventional methods? Placebos are usually defined not in terms of what they are but what they are not. They are often described as inactive, but placebo agents are clearly active: they exert influence and can be quite effective in eliciting beneficial responses. Placebos are also described as nonspecific, presumably because they relieve multiple conditions and because exactly how they work is not fully understood. Yet by either of these standards, placebos are no less specific than many valid and accepted remedies, such as aspirin or certain tranquilizers. Most narrowly, a placebo is a pharmacologically inert capsule or injection, yet even this definition does not capture the full range of procedures that can have a placebo effect.

Today the most common situation in which people use substances known to be placebos is during double-blind clinical trials. Patients who take a placebo in the course of such trials receive much more than a pharmacologically inert substance: like the patients receiving a "real" drug, they benefit from a thorough medical evaluation, a chance to discuss their condition, a diagnosis and a plausible treatment plan. Patients also

Medicine has become vastly more scientific in the past century—gone are the potions, brews and bloodlettings of antiquity.

Nevertheless, doctors and their patients continue to ascribe healing powers to pills and procedures that have no intrinsic therapeutic value.



The placebo effect is not unique to psychiatric illness.

For a wide range of afflictions, 30 to 40 percent of patients experience relief after taking a placebo.

PLACEBOS ARE EFFECTIVE for a variety of conditions. Patients with angina pectoris (insufficient blood flow to the heart) responded to placebo surgery in which doctors made only an incision in the chest but did nothing further (*a*). In a study of patients with generic symptoms but no organic ailment, researchers found that reassuring words from a doctor helped patients to feel better (*b*). And in a study of the drug propranolol, which is used after heart attacks to prevent further damage, investigators noticed that patients who took placebo pills regularly had a lower death rate than patients who took placebos sporadically (*c*).

typically enjoy the enthusiasm, effort, commitment and respect of their doctors and nurses. These factors, which many people view as incidental to the healing process, provide an important clue as to why placebos work.

The healing environment is a powerful antidote for illness. The decision to seek medical assistance restores some sense of control. The symbols and rituals of healing—the doctor's office, the stethoscope, the physical examination—offer reassurance. An explanation for the illness and a prognosis, when favorable, reduce fear; even when the report is unfavorable, it allays the anxiety of uncertainty. And merely the act of taking a pill can have a therapeutic effect. For example, the drug propranolol is often prescribed after a heart attack to regulate the heartbeat and prevent further damage. In a recent study of more than 2,000 patients, the death rate was cut in half among patients who took propranolol regularly compared with those who took the medication less regularly. But in the same study, patients who took placebos regularly also had half the death rate of those who took them less regularly—even though the two groups of placebo users were similar medically and psychologically.

Notably, placebos seem to be most reliably effective for afflictions in which stress directly affects the symptoms: in certain forms of depression and anxiety, for example, distress *is* the illness. And conditions such as pain, asthma and moderate high blood pressure can become worse when the patient is upset. Indeed, placebos may work in part by lessening the apprehension associated with disease. Studies of both animals and humans have shown that the functioning of the immune system falters under stressful conditions. For instance, stress increases the secretion of hormones such as cortisol, which in turn lowers resistance to disease. It is not inconceivable that by reducing anxiety, placebos could influence countless diseases, including some that we do not usually think of as subject to psychological influence.

Great Expectations

A patient's expectation of improvement is also crucial. Researchers know that across a wide range of illnesses, patients who think they will feel better are more likely to do so. Expectation operates more specifically as well. For example, when participants in a study were told that their pharmacologically inert drink contained alcohol, they often felt and acted intoxicated and even showed some of the physiological signs of intoxication. A 1968 study led by Thomas J. Luparello of the State University of New York Downstate Medical Center in Brooklyn showed that patients with asthma who were given an inhaler containing only nebulized saltwater but were told they would be inhaling an irritant or allergen displayed more problems with airway obstruction. When the same group was told that the inhaler had a medicine to help asthma, their airways opened up.

Given their demonstrated effectiveness, why do placebos have such a dubious reputation? The word "placebo" itself comes with unfortunate baggage. Latin for "I shall please," it is the first word of the vespers for the dead, and in the 12th century these vespers were commonly referred to as placebos. By the 1300s, the term had become secular and pejorative, suggesting a flatterer or sycophant, a meaning probably derived from the depreciation of professional mourners, those paid to sing placebos. When the word entered medical terminology, the negative connotation stuck. It was defined as a medicine given to please patients rather than to benefit them. In the modern era, the lack of pharmacological activity became part of the definition as well.

As a result, the name brings with it connotations of deception and inauthenticity. A modern myth about placebos reflects this stigma: if a condition improves with placebos, the condition is supposedly "all in the head." But the many examples of physical ailments—high blood pressure, angina pectoris and asthma, to name a few—that respond to placebos demonstrate that this notion is far from the case.

The very effectiveness of a placebo is troublesome to us doctors and to other medical experts. It impugns the value of

ABRAHAM MENASHE (*photographs*); JENNIFER C. CHRISTIANSEN (*graphs*); SOURCES: (*a*) E. G. DIMOND ET AL., 1960; (*b*) K. B. THOMAS, 1987; (*c*) R. I. HORWITZ, 1990

our most cherished remedies, it hampers the development of new therapeutics, and it threatens our livelihood. Nevertheless, given the astounding advances in medical technology over the past two decades, including the development of indisputably efficacious drugs and procedures, we in the medical community may now be ready—secure that medicine is scientific—to accept and put to good use this component of healing that we do not fully understand.

If physicians can see placebos as broadly effective therapies, whose mechanisms of action are not completely understood and which tend to be more effective for some conditions than others, they can then offer placebos both honestly and as plausible treatment.

Decades of research offer guidance as to how physicians can incorporate aspects of the placebo effect, in ways that are both medically and ethically sound, to make accepted medicines more effective. Yet many of these ideas have not been tried by doctors. Some of the suggestions are not surprising. For instance, patients should be made to feel confident and secure that they are in the hands of a recognized healer; diplomas, board certifications and medical instruments in sight generally provide these signals. Patients should also be reassured by items associated with the relief of symptoms—a white coat, a physical examination, a written prescription when necessary. A careful analysis of a patient's complaint is far more comforting than an immediate diagnosis, no matter how accurate.

Administering a thorough evaluation, however, does not mean that a patient should be subjected to unnecessary diagnostic procedures. Rather the doctor should listen carefully, ask suitable questions and perform a complete examination. The fact that someone has bronchitis may be obvious to a doctor within seconds; an additional five minutes of evaluation that includes a stethoscope on the chest may not add to the accuracy of the diagnosis, but it does add to the patient's confidence. Physicians and nurses of yesterday seemed to understand intuitively the importance of a good bedside manner. Many of today's medical experts still appreciate the healing power of a compassionate consultation, but under pressure to provide "cost-effective" care, they (and particularly insurance companies) may be losing sight of this crucial component of effective care.

The initial evaluation should include specific questions regarding the patient's previous experiences with a variety of remedies, including treatments (such as alternative therapies) most physicians consider to be placebos. What has worked and what has not for this person? In particular, the doctor or nurse should elicit the patient's ideas about what might or might not be helpful for the present complaint.

Determining a Diagnosis

The physician should provide a diagnosis and a prognosis whenever possible. In a recent study of 200 patients with physical complaints but no identifiable disease, doctors at the University of Southampton in England told some that no serious disease had been found and that they would soon be well; others heard that the cause of their ailment was unclear. Two weeks later 64 percent of the first group had recovered, but only 39 percent of the second group had recuperated.

If a specific drug or medical procedure is called for, it should be offered with realistic optimism and information about its specific desirable effects—something along the lines of "This medicine will help you breathe" for an asthma medication. The doctor should also provide information about side effects and about the most likely course of symptoms. This information adds to the patient's confidence and to the sense that the condition is known and controllable.

If a number of treatment options are equally appropriate, the patient should be given the chance to make a choice. But doctors should offer a limited number of options (no more than three or four) and should provide sound information to help the patient in making the decision. Allowing patients—no matter how well informed they may be—to choose whatever course of therapy they would like deprives them of a major benefit of seeking medical advice. If people want to treat themselves, and many do, they do not go to experts.

When managing conditions such as the common cold that typically run their course without treatment or when handling diseases such as certain cancers that have no effective treatment, doctors often prescribe palliative medication to relieve symptoms such as congestion or pain. For these therapies to be most useful, however, it is important that doctors offer them with the same thoughtfulness and authority as when they recommend other, more definitive remedies.

In practice, though, this is not always the case. Doctors often tell patients with colds or the flu that they will probably feel better in a few days and that they can take cold medicine if they want to. Such patients, feeling miserable and bereft of treatment, often request and receive antibiotics—pharmacologically active but inappropriate drugs that they are unwittingly using as placebos. These same patients would very likely feel quite differently if, after a medical examination complete with diagnostic instruments, their doctors wrote the name of a cold medicine on a prescription form (even if the drug did not require a prescription) and handed it to them with

instructions on how and over what interval this medicine will be helpful.

Some of these suggestions may seem like hocus-pocus. Yet I see them as an approach to medicine informed by an understanding of all the processes involved in healing. In the case of the common cold, such an approach could go a long way toward reducing the unnecessary use of antibiotics and the attendant expense and dangers of the practice.

Prescribing Placebos

What about the deliberate use of placebos? Should physicians, in order to take advantage of the placebo effect, prescribe drugs or procedures that they know to be of no intrinsic value?

For many medical experts, this situation presents what has seemed an insolvable dilemma. Doctors have felt that if they tell patients they are prescribing a sugar pill, the placebo response, which depends in part on patients' expectations of receiving a plausible remedy, will be lost. On the other hand, if doctors tell patients that the placebo is a pharmacologically active medicine, they are engaging in a type of deception that is neither ethical nor, in the long run, therapeutic. I think much of this dilemma arises from the pejorative connotations associated with placebos and a general uncertainty about their value.

If physicians can see placebos—like many conventional drugs—as broadly effective therapies, whose mechanisms of action are not completely understood and which tend to be more effective for some conditions than others, they can then offer placebos both honestly and as plausible treatment. The decision to prescribe a placebo should be based, as with any drug, on the risks and benefits. The specific placebo chosen should be free of toxicity and should be in keeping with the patient's beliefs and expectations. In this regard, it is worth noting that, according to a study published in 1993 in the *New England Journal of Medicine,* at least 30 percent of adult Americans use alternative medicine—such as massage, homeopathy, spiritual healing and megavitamins—and that the total number of visits to alternative therapy providers each year exceeds the number of visits to primary care physicians. Although alternative medicine healers and their patients believe fervently in the effectiveness of megavitamins and herbal mixtures, many of these popular remedies probably derive their benefit from the placebo effect.

So how can a doctor ethically prescribe a placebo? Consider a specific example—the treatment of mild to moderately high blood pressure. Clinical trials, such as the study conducted in the early 1990s by Barry J. Materson of the Veterans Affairs Medical Center in Miami, have shown that at least 20 percent of people with this condition achieve normal blood pressure after several weeks of taking placebos. Because blood pressure medication is expensive and has troublesome side effects, some patients might want to consider taking a placebo as a course of treatment.

A doctor could explain the situation to a patient in the following manner: "You have several options. One is to take a diuretic. It will probably bring your blood pressure down, but it does have some side effects. There are also other treatments that are less expensive and less likely to cause side effects and that help many people with your condition. Some find that herbal tea twice a day is helpful; others find that taking these pills twice a day is helpful. These pills do not contain any drug. We do not know how the herbal tea or these pills work. They may trigger or stimulate your body's own healing processes. We do know that about 20 percent of the people with your type of high blood pressure get their blood pressure into the normal range using this approach. If you decide to try one of these treatments, I will check your progress every two weeks. If after six weeks your blood pressure is still high, we should consider the diuretic."

ABRAHAM MENASHE

Disease is typically defined as an abnormal state of the body—high blood glucose, a fractured forearm, a lung infection. But illness is something else: it is the suffering that accompanies disease. In our culture, pills and other symbols of the physician's healing arts have great power to ease that suffering. As physicians, we should respect the benefits of placebos—their safety, effectiveness and low cost—and bring the full advantage of these benefits into our everyday practices. SA

The Author

WALTER A. BROWN has been with the psychiatry department at the Brown University School of Medicine since 1974. About 10 years ago he established a research center in Rhode Island to carry out clinical trials of psychiatric drugs. He is currently working on a study of brain function and measures of immunity during experimentally induced emotion. Brown is a fellow of the American Psychiatric Association and a member of the American College of Neuropsychopharmacology.

Further Reading

PERSUASION AND HEALING. Jerome D. Frank and Julia B. Frank. Johns Hopkins University Press, 1991.

HARNESSING PLACEBO EFFECTS IN HEALTH CARE. D. Mark Chaput de Saintonge and Andrew Herxheimer in *Lancet,* Vol. 344, No. 8928, pages 995–998; October 8, 1994.

THE PLACEBO EFFECT: AN INTERDISCIPLINARY EXPLORATION. Edited by Anne Harrington. Harvard University Press, 1997.

SCALA/ART RESOURCE

Leonardo and the

Leonardo da Vinci's notebooks are full of inventions, from intricate gun parts to bicycles to automobiles. But were any of Leonardo's many creations actually made during his lifetime?

by Vernard Foley

According to legend, the great Italian artist and inventor Leonardo da Vinci died while pleading, "Tell me if anything at all was done." Although historians dispute the specifics of this story, this phrase does appear in Leonardo's notebooks, implying that he regretted he had not accomplished more in his lifetime.

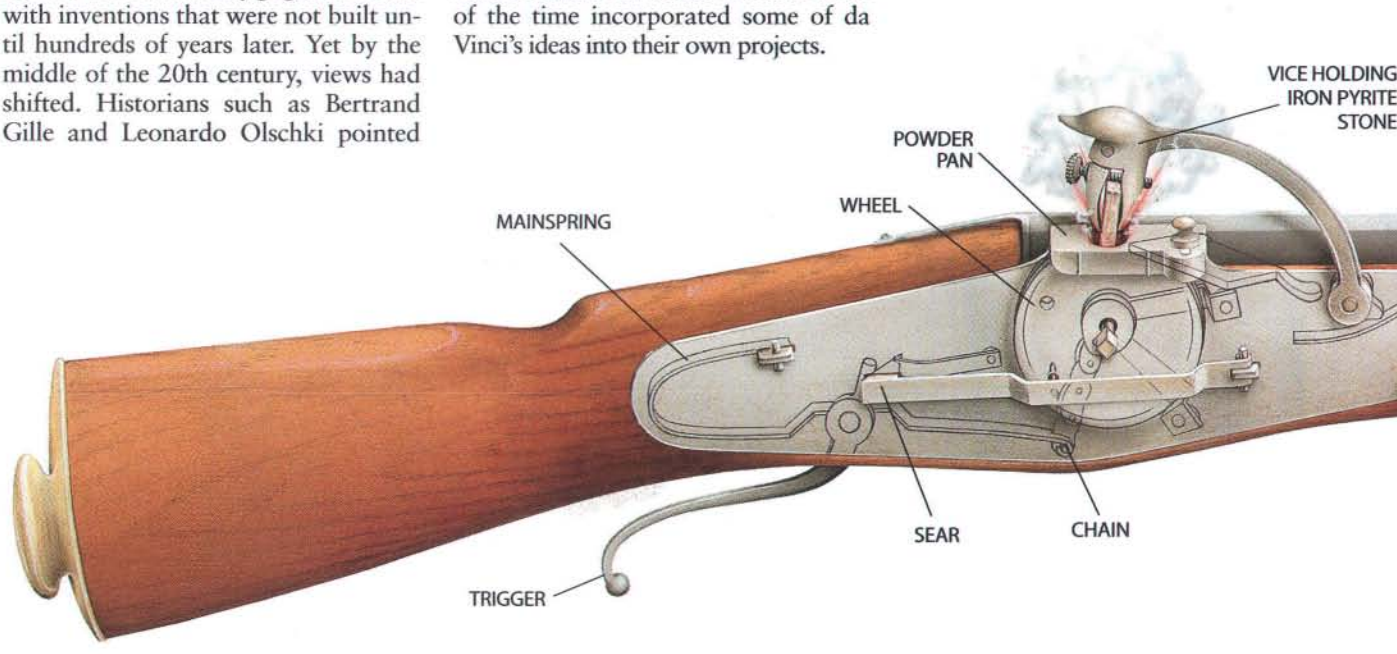
The question of how much Leonardo achieved during his 67 years (1452–1519) has resurfaced among current scholars of Renaissance engineering. When Leonardo's manuscripts were first published at the end of the 1800s, readers were amazed by pages crammed with inventions that were not built until hundreds of years later. Yet by the middle of the 20th century, views had shifted. Historians such as Bertrand Gille and Leonardo Olschki pointed out Leonardo's great debt to earlier Renaissance engineering manuscripts and suggested that he was merely a derivative figure.

Leonardo's reputation began to recover after more of his notebooks were found in the 1960s and published as the *Madrid Codices*. The original editor of the collection—the Italian historian Ladislao Reti—and his successor Augusto Marinoni, as well as the wealthy American collector and historian Bern Dibner all found examples in the notebooks of original designs and experimental work by Leonardo. The researchers also uncovered evidence that craftsmen of the time incorporated some of da Vinci's ideas into their own projects.

Nevertheless, the question remains whether any of Leonardo's fundamental inventions ever got off paper and into production in his lifetime. It appears at least one item did—the wheellock.

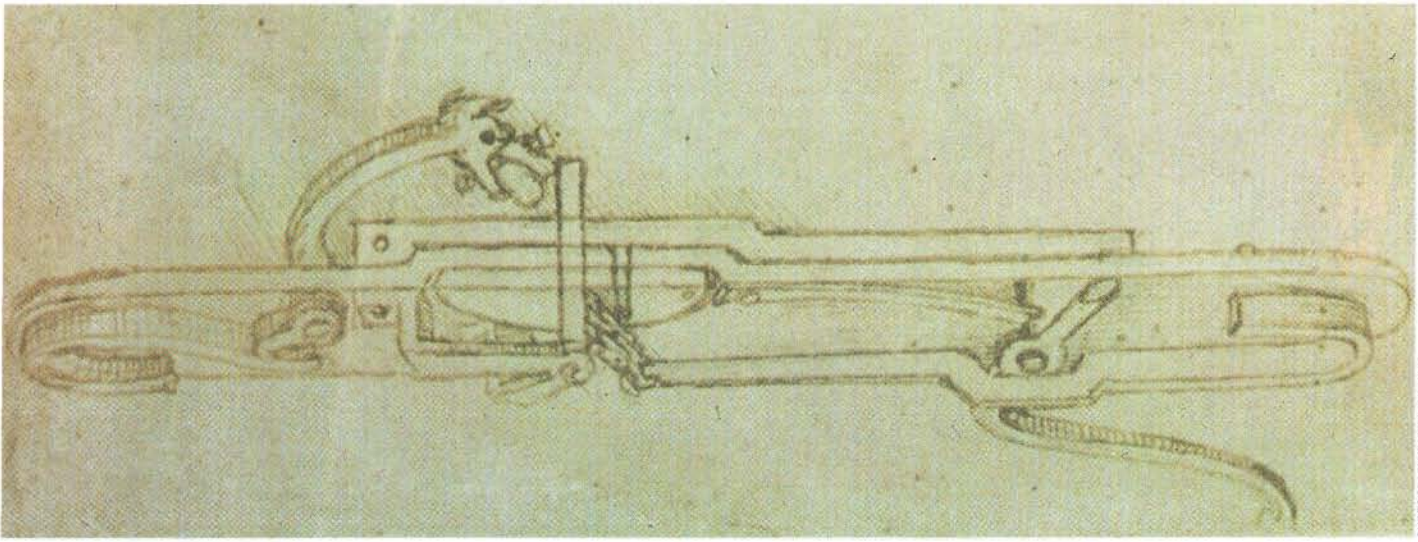
Wheellock, Stock and Barrel

The wheellock is a small metal mechanism that supplies the spark for igniting flammable compounds, particularly gunpowder. In a modern variant the wheellock can be found on most cigarette lighters. In Leonardo's day, however, the wheellock was mainly used



TOMO NARASHIMA

Invention of the Wheellock


PHOTOGRAPH BY BETH PHILLIPS

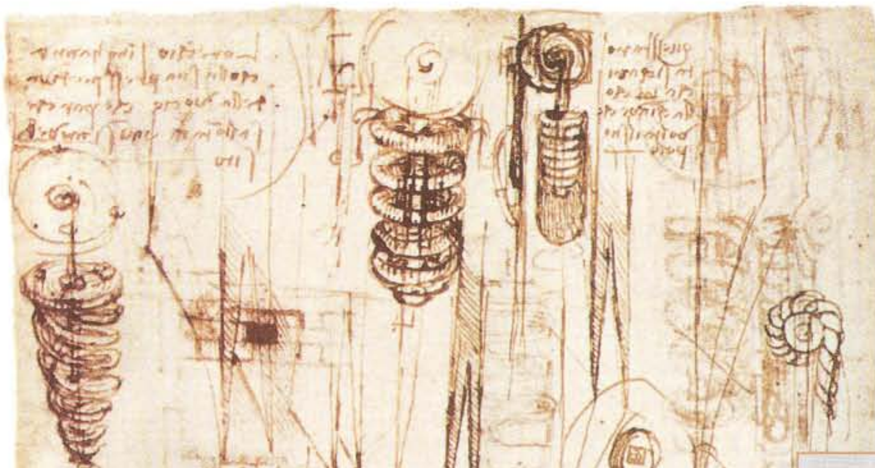
on small guns, such as muskets, that could be carried and fired by one person. These guns consisted of three parts: the familiar lock, stock and barrel. The gun's long cylindrical barrel held the powder and the bullet and launched the shot when the gun was fired. The lock sat at the rear of the barrel, and the stock was the wooden part of the gun that held the other two parts together.

Some of the components of the wheellock resemble those of a door lock; this similarity probably explains the name. A wheellock consists of a steel wheel with a chain attached to its axle linking the wheel to a powerful spring. Together the chain and the spring wind up the wheel in preparation for firing. Once the wheel is wound fully, a latch (often called a sear) holds the wheel in place until it is released when the trigger is pulled. Then, as the wheel begins to spin, it scrapes against a hard stone, typically iron pyrite, pressed firmly against the spinning wheel by a second spring. During this process, internal friction heats the scrapings to incandescence. The top of the wheel rim fits into a powder holder (called the pan) through a thin slot in its base. The heat from the sparks sets fire to a charge of gunpowder inside the powder pan.

Although several surviving sketches of Leonardo's have led some historians to argue that da Vinci invented the wheellock, others disagreed. The naysayers held that the earliest documented production of the wheellock occurred farther north, in what is now Germany. These researchers concluded that Leonardo must have drawn his own version of the lock only after hearing of the German developments.

Until recently, the available evidence on this question has been somewhat inconclusive. The first German illustrations of wheellocks, from the early 1500s, are rather close in date to Leonardo's sketch-

DESIGN OF A WHEELLOCK from Leonardo da Vinci's *Codex Atlanticus* (*top of page*) shows a cross section through the middle of the axle of the wheel. To prepare a gun with a wheellock for firing (*above*), a vice holding an iron pyrite stone is lowered until it rubs against the wheel, which connects to the mainspring through a short, flat-link chain attached to the wheel's axle. The wheel is locked in place when cocked by a latch, or sear. When the trigger is pulled, the latch is released, and the wheel starts to spin and scrape against the iron pyrite stone, generating sparks.



NEW YORK PUBLIC LIBRARY; COURTESY OF VERNARD FOLEY (*inset*)

SKETCHES from the *Codex Atlanticus* show two types of wheellock components: the helical springs and a number of flat-link chains, visible in faint ink bleed from the other side. Helical springs seem to have interested Leonardo because they are less bulky than the so-called flat-leaf springs common in his time. Across the top of the page, da Vinci drew a series of V-shaped chisels whose angles become wider moving right to left (the left-handed Leonardo typically wrote from right to left). A side view of the chisel, the next in the series, with the V shape lying on the chisel's bottom surface, appears at the lower right, where it appears to be cutting on the edge of a circle—probably a wheellock wheel. The author has used similar chisels to re-create the grooves (*inset*) commonly found around the rims of early wheellock wheels.

es, and written references to the lock, as well as the few surviving guns from the period, are also difficult to interpret. A fresh approach to this problem, however, provides evidence that Leonardo should be given credit for the invention, as he began working on the wheellock in or near the year 1493.

Chains and Chisels

In particular, I have analyzed early wheellocks from a mechanical point of view, paying close attention to the shape of individual components. It appears that da Vinci utilized components from other machines that he had worked on in the 1480s and 1490s—such as door locks and bicycles—and put them together in a fundamentally new way to create the wheellock.

Consider first a page from the *Codex Atlanticus*, another compilation of Leonardo's manuscripts, which is now housed in Milan. This page [*see illustration above*] contains sketches of the types of chains and springs found in wheellocks. All da Vinci scholars agree that these drawings prove he knew of the device. The page also includes images of V-shaped chisels for woodcutting, which Leonardo was apparently trying to adapt for cutting metal.

The chisels Leonardo drew are especially noteworthy. The V shape of these chisels would have produced a V-shaped groove (similar to the thread of a screw) along the rim of the wheel. The wheel rims of early wheellocks typically had several of these grooves. In addition, the rims usually bore a second set of very narrow file-cut grooves that ran across the threads around the rim and were spaced in such a way to form, in effect, a tiny set of teeth like those on a rotary saw. At first sight this arrangement seems unduly complex, because each of the threads would have to be individually carved out of the powder pan as well. Furthermore, the cross grooves can interfere with good ignition.

The advantages of this design became apparent, however, when I tested some sample wheels and found that the teeth really are like those on a saw or rotary metal cutter. The wheel can actually cut its own slot into the bottom of the metal pan holding the gunpowder, ensuring a snug fit. Such a close connection is crucial because the priming powder is extremely fine-grained, and if the gun were jostled at all (say, when it was carried by someone on horseback) the powder could dribble away through any gap between the wheel and the pan. Although these 15th-century saws are slow—it takes them several hours to do what modern cutters can accomplish in seconds—their accuracy is as good as today's technology. It is not difficult for them to hold tolerances closer than 0.3 millimeter (0.01 inch).

Before this discovery, the first use of rotary metal cutters had been dated to the 1540s, long after Leonardo's death. Yet it appears that Leonardo should be credited with the development of these cutters—quite a remarkable achievement considering that the modern milling machine, which incorporates this tool, is one of the most important manufacturing devices in existence today.

Although Leonardo's work with springs, chains and chisels certainly

demonstrates that he knew of the components of the wheellock, the question remains as to when he assembled them to invent the device. In 1493 Leonardo took into his employ Giulio Tedesco, also known as Jules the German, who served for some years as a technician in Leonardo's studio in Milan. Scholars do not know precisely when Giulio left Milan, but it was probably no later than 1500. Remarks by Leonardo indicate that Giulio's specialty included door locks and other spring-powered mechanisms, such as crossbows and shears.

Partners in Design

Leonardo's drawings from the same time of locks for doors or chests contain components that closely echo the shapes of wheellock parts. These similarities hint that the wheellock was developed by Leonardo and Giulio working together in the mid-1490s. In addition, Jules the German could have taken the design of the wheellock back to his native land after leaving Leonardo, thereby explaining how the contrivance reached northern Europe in the early 1500s.

The historian Claude Blair, formerly of the Victoria and Albert Museum, has recently uncovered important additional evidence that da Vinci invented the wheellock. Blair has determined that in the city of Cividale in the state of Friuli in the north of Italy, the manufacture of wheellocks began at least by 1510 and probably several years before. Leonardo worked in Friuli for a time, doing surveys for castle fortifications no later than 1500, thus predating any German claim to the mechanism.

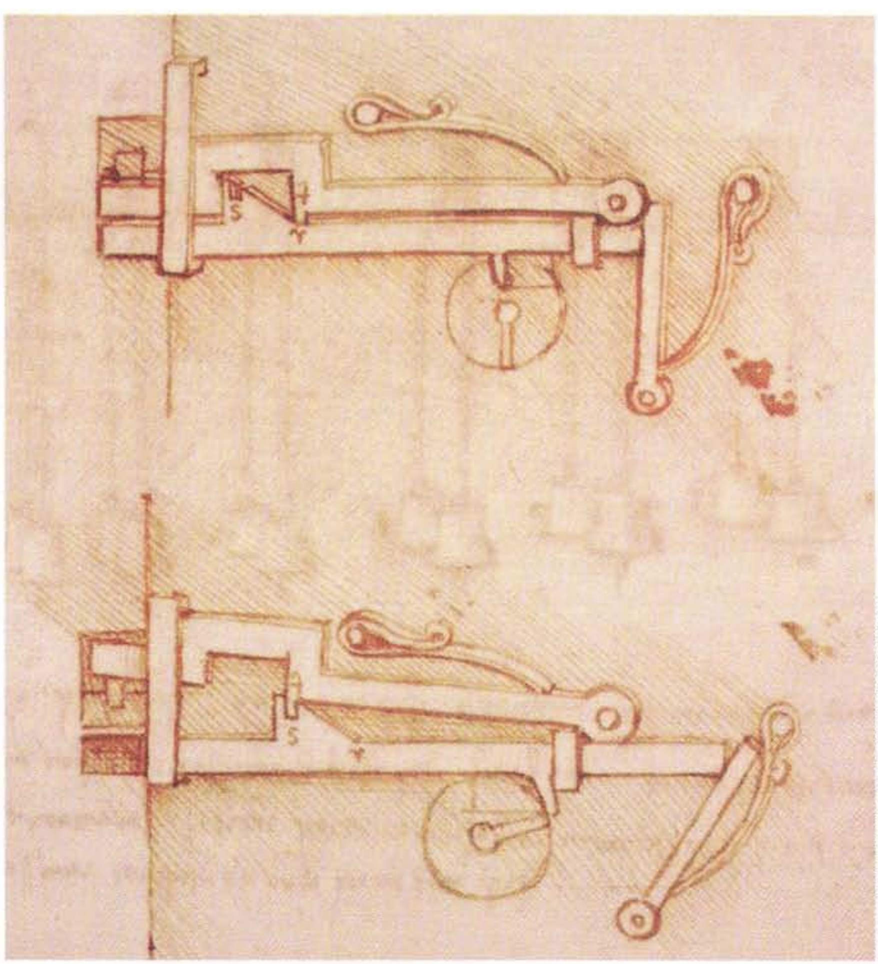
Leonardo's claim to inventive priority has not been the only question touched on in these investigations into the origins of the wheellock. I have also learned something of how he would borrow from existing machines and rearrange their components to produce new instruments. This process can be seen most clearly by looking further at his sketches of door locks and bicycles.

To open his locks for chests and doors against the pressure of their strong closing springs, Leonardo sometimes designed them with so-called cocking keys, which were separate from the keys needed to unlock the mechanism and were used to compress the springs in the lock. These keys were usually shaped like a wing nut or butterfly nut, often with perforations in each wing. Some of the early wheellocks also have such keys pinned to the wheel for cocking the lock. Another similarity between Leonardo's door locks and wheellocks can be seen in the latches that hold the springs under strain. In da Vinci's drawings, latches for both door locks [*see illustration below*] and wheellocks are formed from a bar with a notched triangular protrusion on one side and an additional small pin.

Leonardo also worked on the design of the bicycle during the 1490s. Some of the flat-link chains and braking mechanisms in his bicycles turn up again in his wheellocks. A crude sketch of a bicycle found in Leonardo's notebooks has been attributed to one of his students but is believed to reflect da Vinci's previous work on the bicycle and its parts. There are several problems with this drawing—in particular with the pedals, the steering system and the drive chain mechanism.

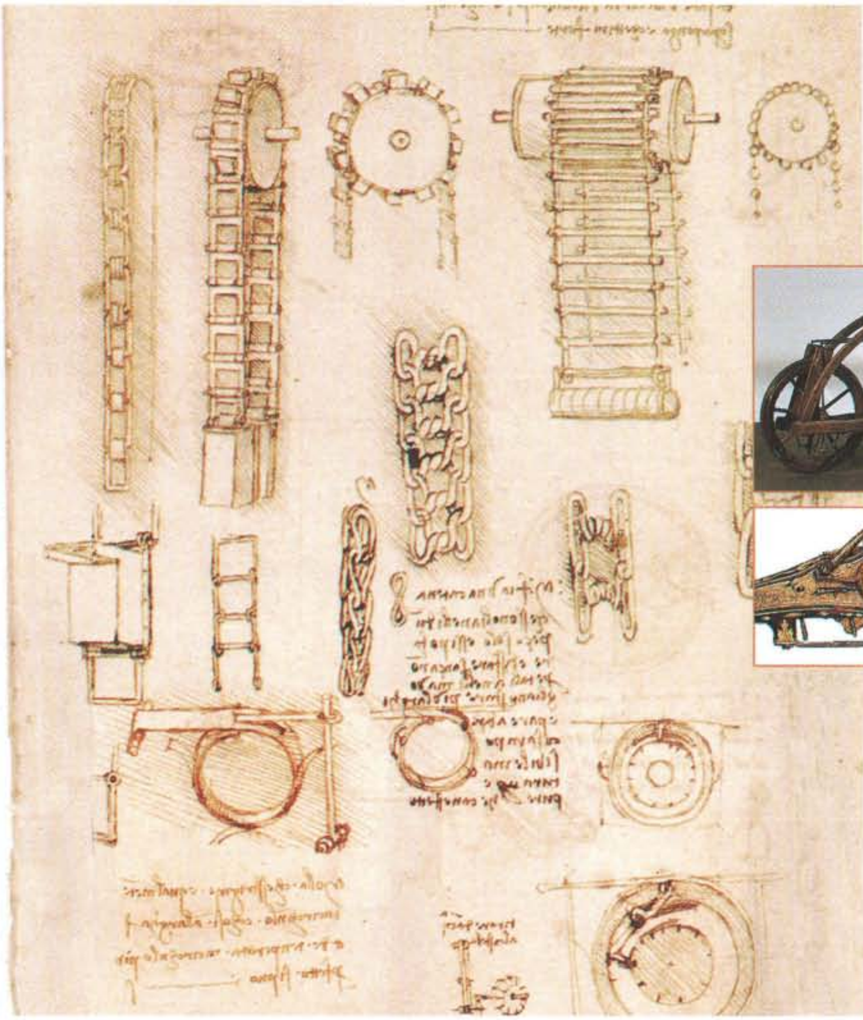
Some of my former students at Purdue University (Edward Blessman, Jim Bryant and Kyle Datesman) and I have interpreted additional sketches—from the 1490s and in da Vinci's own hand—that enabled us to reconstruct a sophisticated steering system for his bicycle. Two pages from the *Codex Madrid* illustrate steering components and experimental drive chain designs. In addition, Leonardo has drawn what appears to be sets of coaster brakes for his bicycle, which enable it to roll without pedaling [*see illustration on next page*]. Significantly, both the drive chain mechanisms and the braking spring from his bicycle reappear in his early wheellocks.

The invention of the wheellock was truly a momentous achievement. Previous gun locks—namely, the matchlock—relied on external heat sources, such as glowing embers or lit matches, to ignite



INSTITUTE AND MUSEUM OF THE HISTORY OF SCIENCE, FLORENCE

SKETCHES OF DOOR LOCKS found in the *Codex Madrid* date from when Giulio Tedesco, a German technician, worked with Leonardo in Milan. These drawings show latching bars designed to keep the bolt open against the pressure of strong closing springs. These bars resemble the sears used on wheellocks. Both types of bars carry notched triangular projections and smaller, shorter projecting pins that hold the cocked mechanisms in place.



INSTITUTE AND MUSEUM OF THE HISTORY OF SCIENCE, FLORENCE; NAJLAH FEANNY *Saba* (*top inset*); METROPOLITAN MUSEUM OF ART, GIFT OF WILLIAM H. RIGGS, 1913 (*bottom inset*)

BICYCLE PARTS reappear in Leonardo's wheellocks. The gears and chains at the top of this illustration (from the *Codex Madrid*) are very similar to chains connecting the axle and the mainspring in the wheellock. The author's former student Kyle Datesman has built a working model of a bicycle (*top inset*) by incorporating several of Leonardo's other components depicted in his notebooks—the steering system shown on an adjacent page and the band brakes shown at the bottom of this sketch. These brakes function like modern coaster brakes, letting the bike roll without pedaling but also allowing the rider to stop. The shape of the band brakes reappears in early wheellocks (*bottom inset*).

the gunpowder. After the introduction of the wheellock, guns could be concealed yet kept ready for instant action, without having to pause to light a match. This advance toward more convenient guns would forever alter the role these weapons played in society.

The first recorded accidental discharge of a gun—an event facilitated by the invention of the wheellock—occurred in 1515 in the town of Constance, Germany, according to the original account by a German writer of the time, Wilhelm Rem. A man named Laux Pfister hired a prostitute, and "when she was with him in a little room, he took up a loaded gun in his hand, the lock of which functioned in such a way that when the firing mechanism was pressed, it ignited itself and so discharged the piece." Pfister was playing around with the gun when it went off, shooting the woman through the chin. As punishment, he had to pay the woman's medical bills and provide her with a fixed income every year for the rest of her life.

The increasing number of wheellock guns brandished by highwaymen and other brigands led authorities to pass edicts against the manufacture and operation of wheellocks. But emerging evidence suggests that both gunmakers and the wielders of firearms evaded these laws, and in the long run the efforts at gun control proved inadequate. Mundane factors, such as the cost, reliability and demand for wheellock guns, determined how these devices were used.

In the centuries since Leonardo's time, advances in gun manufacturing have influenced other areas; the most notable of these contributions is surely the technique of mass production with interchangeable parts. From such small beginnings as fitting a spinning wheel to a powder pan, much has grown, and Leonardo's query as to whether anything at all was done can indeed be answered in the affirmative. SA

The Author

VERNARD FOLEY teaches courses in the history of engineering and science at Purdue University. His interests include the development of manufacturing techniques, the evolution of economic thought, as well as issues regarding Native Americans and the environment. He is impressed by the influence of technology on pure science and finds that actually constructing devices made in the past can convey insights obtainable in no other way. This article is Foley's sixth publication in *Scientific American*.

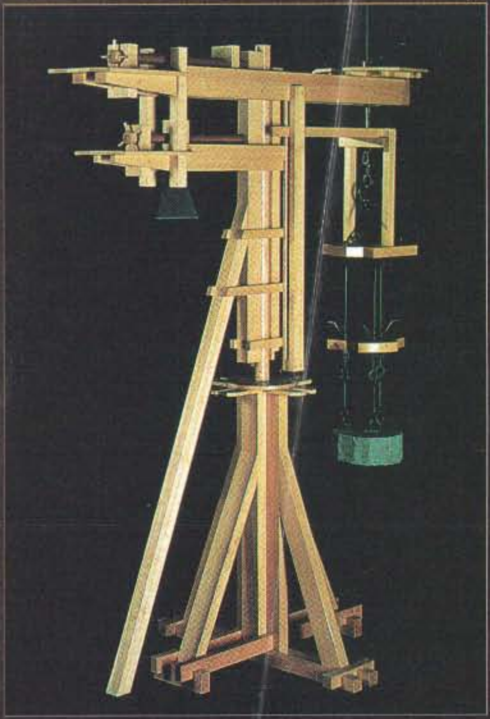
Further Reading

LEONARDO DA VINCI UND DAS FAHRRAD. (English summary included.) Vernard Foley, Edward R. Blessman and James D. Bryant in *Technikgeschichte*, Vol. 50, No. 2, pages 100–128; 1983.

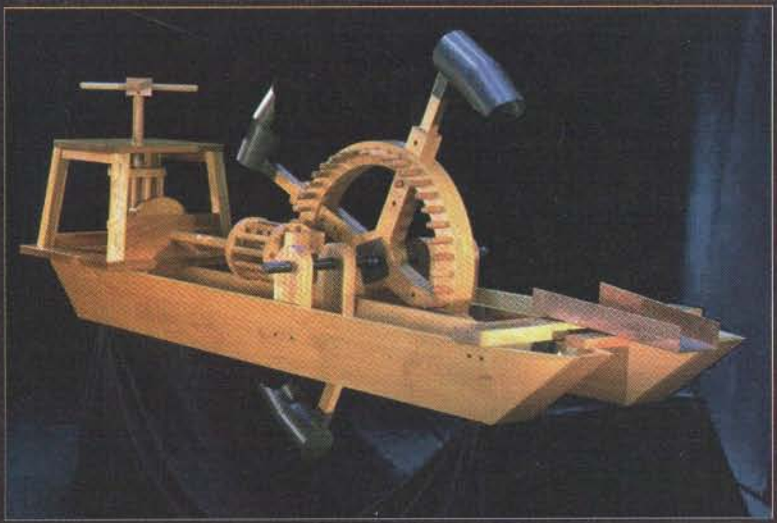
LEONARDO, THE WHEELLOCK, AND THE MILLING PROCESS. Vernard Foley, Steven Best, David Cassidy and F. Charles Logan in *Technology and Culture*, Vol. 24, No. 3, pages 399–427; July 1983.

THE INVENTION OF THE WHEELLOCK. Vernard Foley in *Journal of the Arms and Armour Society*, Vol. 11, No. 4, pages 207–248; 1984.

NEW LIGHT ON THE EARLY HISTORY OF THE WHEELLOCK IN ITALY. Claude Blair in *Waffen- und Kostumkunde*, Vol. 37, Nos. 1–2, pages 27–52; 1995.



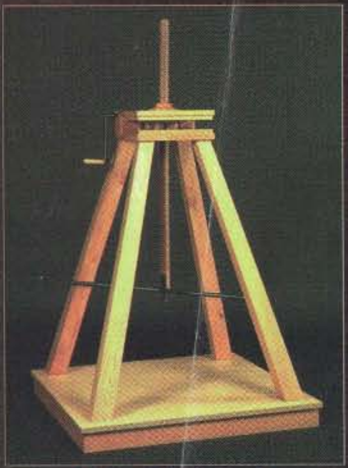
Leonardo da Vinci
BRUNELLESCHI'S REVOLVING CRANE



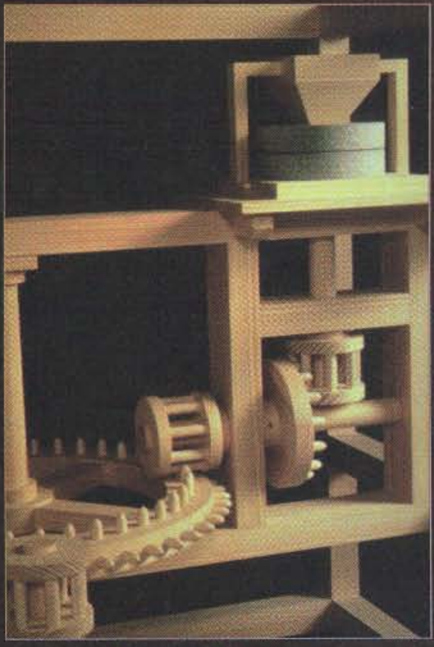
Francesco di Giorgio
MUD EXTRACTOR

Renaissance Technology

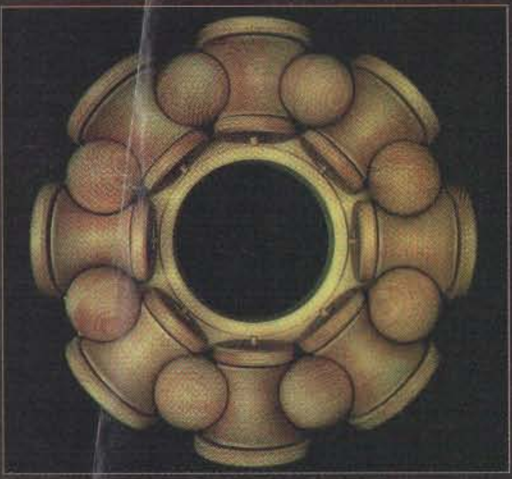
After stops in Paris and Florence, the international exhibit *Mechanical Marvels: Invention in the Age of Leonardo* opened in New York City in October 1997 at the Liberty Street Gallery at the World Financial Center. The show, which will run until March 1998, features 50 working models of the machines designed (but not always built) by several prominent Renaissance inventors. Several of the inventions re-created for the exhibit are shown here. —*The Editors*



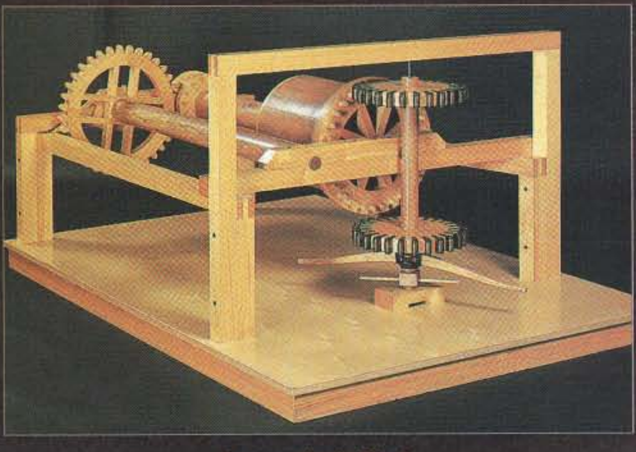
Leonardo da Vinci
SCREW JACK WITH
ANTIFRICTION BEARING



Francesco di Giorgio
HORIZONTAL-WATERWHEEL MILL



Leonardo da Vinci
PRESSURE-RESISTANT BALL BEARING



Leonardo da Vinci
THREE-SPEED HOIST

by Shawn Carlson

A Kitchen Centrifuge

Biochemists have always amazed me. Using mostly straightforward, inexpensive methods, these gifted researchers somehow manage to unlock many of the mysteries of life. And although the past decade has seen powerful (and expensive) new techniques brought to bear, discoveries are still being made by means that are well within the reach of a dedicated amateur. Sadly, biochemistry is a field that has so far been little explored by amateur researchers, and I think I know why. Few of them have access to what is perhaps the central tool of biochemistry—the centrifuge.

A centrifuge rapidly spins several small test tubes filled with a liquid suspension that is to be separated into its component parts. Like passengers in a car making a high-speed turn, every particle suspended within the tube is thrown outward by its own inertia. Biochemists often take advantage of this effect by adding something to a solution that causes certain components to precipitate. For purifying proteins, for example, this change is often provoked by adding a weak acid or base (vinegar or baking soda, for instance). The high "g forces" generated by the centrifuge then induce the solid particles to settle out in no time flat.

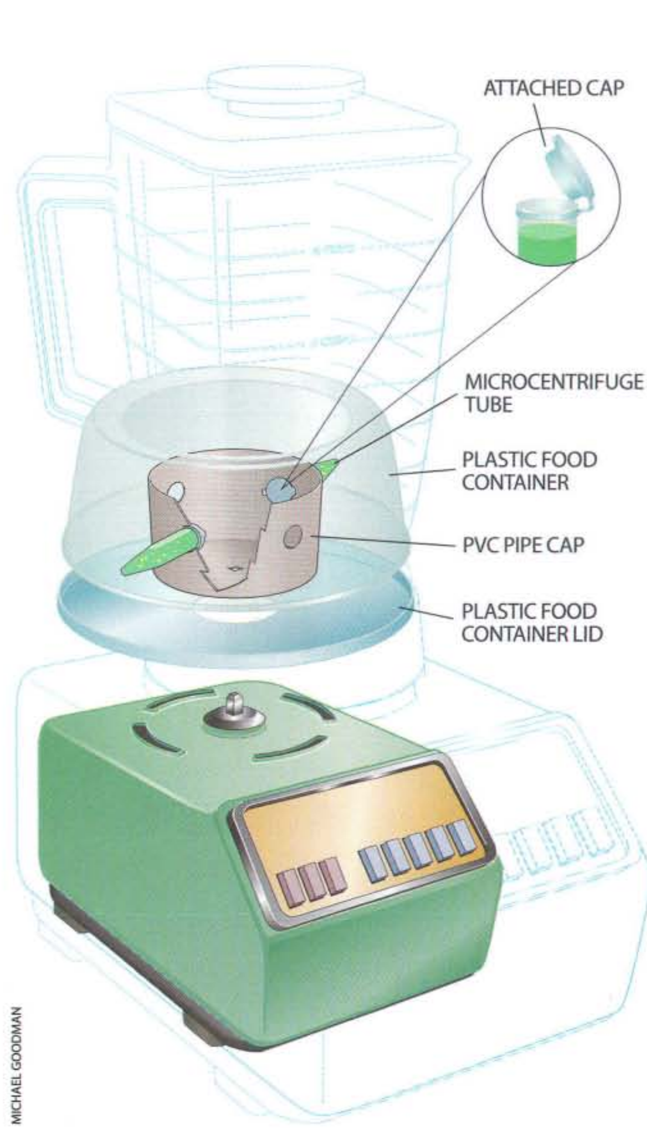
There is no other method that can quickly isolate relatively large quantities of key biochemicals. So whether you want to extract cultured bacteria from their incubating broth, purify proteins or isolate antibodies, you are going to need a centrifuge. Unfortunately, professional models can cost thousands of dollars.

To overcome that financial obstacle, Charles Carter, an amateur biochemist and innovative entrepreneur in London, Ontario, designed a centrifuge that is inexpensive and easy to build. Thanks to his cleverness, any amateur can now construct a practical centrifuge in an afternoon for about $20, using an old kitchen blender, a small plastic pipe fitting and a plastic food storage container. Carter fashioned his prototype from an Osterizer brand of blender, but his technique can be adapted to work with just about any make and model.

Carter's centrifuge (or more correctly, "microcentrifuge," because it uses miniature plastic tubes to hold the samples) consists of three parts: a motorized base, a rotating inner cylinder with the sample tubes, and a fixed outer barrier, which protects you and your family from the high-speed motion inside. Before building this device, you will need to secure a set of miniature sample tubes. Suppliers are listed on the opposite page.

Most blenders have a ringlike plastic piece directly at the top of the base. Cut this piece away from the base with a saw and smooth any jagged edges with sandpaper. Then fashion the protective housing using a large plastic food storage container, one that is at least 20 centimeters (eight inches) in diameter and 10 centimeters (four inches) deep. Cut a large hole in the center of the lid and glue it upside down on the base using Krazy Glue or a similar product so that the rotating shaft pokes up through it. Make sure that none of the glue gets on the rotating parts or blocks any air vents, which help to cool the electric motor.

The centrifuge rotor itself is fashioned from a PVC pipe cap, which is basically a short plastic cylinder with one end closed off. Select one from your local hardware store that is about 10 centimeters in diameter. Make sure the plastic is at least 0.3 centimeter ($^{1}/_{8}$ inch) thick and that it is stiff and inflexible. Carefully drill a hole halfway up the side of the cap using sequentially larger drill bits until the hole is just wide enough to hold one of your miniature sample tubes. Repeat this process three more times to create a total of four holes equally spaced around the circumference.



***OLD BLENDER** can be transformed into an inexpensive home centrifuge for biological experiments.*

The motor shaft must be aligned directly through the center of mass of the cap, which might not lie exactly at its geometric center. To find the right place to drill, suspend the cap from a short length of string so that its flat surface hangs at right angles to the floor. The center of mass lies somewhere along the line running straight down from the suspension point. To find out exactly where to drill, coat the string of a carpenter's plumb bob with colored chalk and align it with the other string from which the PVC pipe cap hangs. Carefully edge the string from the bob as close as possible without touching the cap's flat surface. If you hold the string in place just under the cap and then pluck it so that it snaps lightly onto the plastic surface, the string will leave a chalk line that crosses the point where you need to drill. Repeat this process at least twice more, suspending the cap from other points along the side. The multiple chalk lines will then intersect at the point where you should put the hole.

Next, you must drill precisely through the point you've found, making sure the hole is exactly vertical. A drill press works best here, but with a little care, you can do it with a handheld electric drill. The shafts of many old blenders have metal fittings with square cross sections, which will not fit your round hole very well. Carter simply drilled out a round hole that was just large enough to accommodate the square fitting. Then he doped the metal skirt at the base of the fitting with Krazy Glue, pressed the pipe cap down over it until it set and finally filled the gaps between the fitting and the cap with many applications of glue, letting the assembly harden overnight.

Depending on the design of your blender, you may have to cut a sizable hole in the end cap to accommodate a large plastic fitting on the shaft. In that case, use a hole saw to enlarge the first hole you drilled. Then glue the end cap to the plastic fitting using a carpenter's level to ensure that the cap is not canted. You might also find that an adhesive such as Plastix (Loctite Co., item no. 82565) works better than Krazy Glue.

When the glue sets, you will be ready to test the rotating cap for balance. Place an empty sample tube into each of the four holes and quickly pulse the motor at its lowest setting, being careful to keep your fingers out of harm's way. Should the device rattle loudly and quiver across the table, you will have to make some adjustments. Carter's clever method was to take out each tube in turn and repeat the test. If removing one tube reduces the shaking, you will know to shave some mass from the corresponding side of the cap. Gently file away some plastic from the rim of the cap, directly above the appropriate sample tube. Continually pulse the centrifuge to check on your progress until the cap spins without excessive vibration.

If you want, you can take your apparatus to a motor repair shop, where, for a small fee, a technician should be able to determine the rotation rate for each setting of the blender. (How much faster is "puree" than "mince" anyway?) With this information, you can calculate the precise accelerations your samples experience with the formula given at the left.

To test your centrifuge, fill two clean sample tubes with one milliliter of milk each. Top off one with water and the other with vinegar (5 percent acetic acid). Place the samples into opposing holes so that their lids are inside the rotating PVC cap and their hinges are downward. (Never run the centrifuge with just one tube of liquid, because it would be unbalanced.)

Put on the protective plastic cover and spin for three minutes at the lowest setting. When the rotor comes to a complete stop, remove the cover, extract the tubes and observe what's inside. You'll find that the white of the milk has settled to the bottom of the tube containing the vinegar. This is because the acid has lowered the pH, causing the casein protein molecules, which give milk its white color, to precipitate. Pouring off the remaining solution will leave you with a solid slug of pure protein—a visible token that you have entered the wild world of biochemistry.

Measuring Acceleration

The acceleration, a, to which an object is subjected as it moves in a circular path of radius r and at frequency f is given by

$$a = (2\pi f)^2 r$$

The acceleration caused by gravity (approximately 9.8 meters/second^2 at the surface of the earth) provides a convenient unit of acceleration—one "g." Because motor speeds are usually given in revolutions per minute, and the radius (out to the tip of the rotating sample tube) is best measured in centimeters, the expression becomes

$$a_g = \left(2\pi \frac{f/_{\text{min}}}{60\ {}^{\text{sec}}/_{\text{min}}}\right)^2 \frac{1}{9.80\ {}^{\text{m}}/_{\text{sec}^2}} \frac{r\ \text{cm}}{100\ {}^{\text{cm}}/_{\text{m}}}$$

which, simplified, gives

$$a_g = 1.12 \times 10^{-5} f^2 r$$

(with f in rotations per minute and r in centimeters). Use this formula to convert the rotation speeds for different settings of the blender into the number of g units experienced by your samples.

For more information about this and other amateur science projects, visit the Society for Amateur Scientists's Web site at www.thesphere.com/SAS/. You may also write the society at 4735 Clairemont Square, Suite 179, San Diego, CA 92117, call (619) 239-8807 or leave a message at (800) 873-8767.

Correction: After the December 1997 Amateur Scientist went to press, the rules governing the FINDS prize, renamed the Cheap Access To Space (CATS) prize, were changed. The organizers offer $50,000 for the first group to achieve 120 kilometers altitude and $250,000 for the first to reach 200 kilometers.

Suppliers

Fisher Scientific
http://www.fisher1.com
(800) 766-7000 or (973) 467-6400
(800) 926-1166 (fax)
Catalogue no. 05-406-22
600 tubes for $14.06

Scientific Supply Source
15201 E. Moncrieff Pl., Suite C
Aurora, CO 80011
(800) 377-8775 or (303) 375-1664
Catalogue no. 265-1550
500 tubes for $13.95

by Ian Stewart

Double Bubble, Toil and Trouble

The dodecahedron has 20 vertices, 30 edges and 12 faces—each with five sides. But what solid has 22.9 vertices, 34.14 edges and 13.39 faces—each with 5.103 sides? Some kind of elaborate fractal, perhaps? No, this solid is an ordinary, familiar shape, one that you can probably find in your own home. Look out for it when you drink a glass of cola or beer, take a shower or wash the dishes.

I've cheated, of course. My bizarre solid can be found in the typical home in much the same manner that, say, 2.3 children can be found in the typical family. It exists only as an average. And it's not a solid; it's a bubble. Foam contains thousands of bubbles, crowded together like tiny, irregular polyhedra—and the average number of vertices, edges and faces in these polyhedra is 22.9, 34.14 and 13.39, respectively. If the average bubble did exist, it would be like a dodecahedron, only slightly more so.

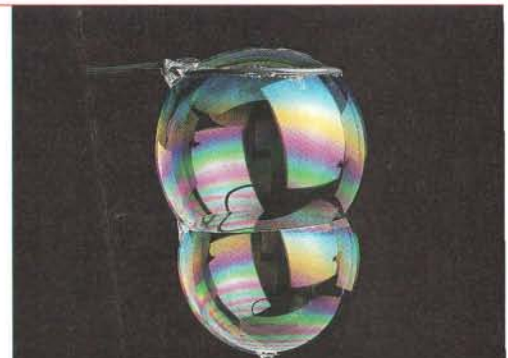
Bubbles have fascinated people ever since the invention of soap. But the mathematics of bubbles and foam only really got going in the 1830s, when Belgian physicist Joseph A. Plateau began dipping wire frames into soap solution and was astounded by the results. Despite 170 years of research, we still have not arrived at complete mathematical explanations—or even descriptions—of several interesting phenomena that Plateau had observed.

A notorious case is the Double Bubble Conjecture, which states that the shape formed when two bubbles coalesce consists of three spherical surfaces. In 1995 Joel Hass of the University of California at Davis and Roger Schlafly of Real Software in Soquel, Calif., announced a proof of this conjecture in the special case when both bubbles enclose the same volume, but the case of unequal volumes remains open. Many other phenomena found by Plateau, however, are now well understood, and experiments with soap films have repeatedly helped mathematicians develop rigorous proofs of important geometric theorems.

In 1829 Plateau had carried out an optical experiment that involved looking at the sun for 25 seconds: this damaged his eyes, and eventually he became blind. Despite his loss of vision, he continued to make major contributions to that most intensely visual area of mathematics, three-dimensional geometry.

Soap bubbles and films are examples of an immensely important mathematical idea called a minimal surface. This is a surface whose area is the smallest possible, subject to certain additional constraints. Minimal surfaces relate to bubbles because the energy caused by surface tension in a soap film is proportional to its area. Nature likes to minimize energy—so bubbles minimize area. For example, the surface of smallest area that encloses a given volume is a sphere, and that's why isolated soap bubbles are spherical.

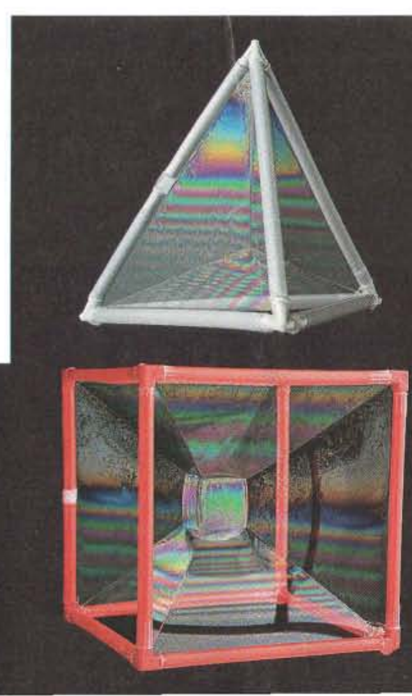
A soap film is so thin—about a millionth of a meter—that it closely resembles an infinitely thin mathematical surface. (Moving bubbles are another matter, because dynamical forces can make them wobble into all kinds of fantastic shapes.)



COALESCING BUBBLES that enclose unequal volumes have shapes that remain a mathematical challenge.

Without some constraint, the area of a minimal surface would be zero. The most common constraints are that the surface should enclose some given volume or that its boundary should lie on some given surface or curve, or both. A bubble that forms against a flat tabletop, for example, is usually a hemisphere, and this is the smallest area surface that encloses a given volume and has a boundary lying in a plane (the top of the table).

Plateau was especially interested in surfaces whose boundary was some chosen curve. In his experiments the curve was represented by a length of wire bent into shape or several wires joined together in a frame. What, for instance, is the shape of a minimal surface whose boundary comprises two identical parallel circles? A first guess might well be



SURFACE OF LEAST AREA is always formed by a bubble. As a result, the soap film joining two parallel circles has the shape of a catenoid. A tetrahedron and a cube give rise to complicated arrangements of nearly flat surfaces that meet at characteristic angles.

PHOTOGRAPHS BY MICHAEL DALTON *Fundamental Photographs*

that it is a cylinder. But we can do better. Leonhard Euler proved that the true minimal surface with such a boundary is a catenoid, formed by revolving a U-shaped curve known as a catenary about an axis running through the centers of the two circles.

The catenary is the shape formed by a heavy, uniform chain hanging between two hooks of the same height: it looks rather like a parabola but has a slightly fatter shape. (A hoary mathematical joke goes, "How do you make a catenoid?" Answer: "By pulling its tail.") Euler's theorem can be demonstrated by making two circular wire rings, with handles—like fishing net frames. Hold them together, dip them into a bowl of soap solution or detergent, and gently pull them apart to reveal the catenoid in all its glistening beauty.

One of the most famous descriptions of soap films can be found in the classic *What Is Mathematics?* by Richard Courant and Herbert Robbins (Oxford University Press, updated in 1996). They relate some of Plateau's original experiments, in which he dipped wire frames shaped like regular polyhedra. The simplest case, which they don't discuss, arises when the frame is a tetrahedron, a shape with four triangular sides and six equal edges. Here the minimal spanning surface consists of six triangles, all meeting at the center of the tetrahedron.

A cubic frame leads to a more complicated arrangement of 13 nearly flat surfaces. The tetrahedron case is fully understood, but a complete analysis for the cube remains elusive.

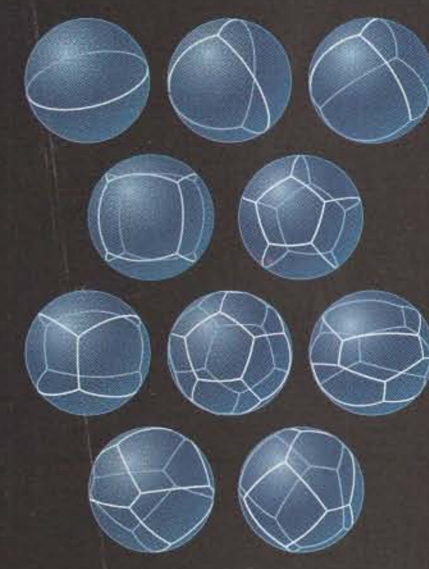
The tetrahedral frame illustrates two general features of soap films, observed by Plateau. Along the lines running from the vertices of the frame to its central point, soap films meet in threes, at angles of 120 degrees; at the central point, four edges meet at angles of 109 degrees 28 minutes. These two angles are fundamental to any problem in which several soap films abut one another. Angles of 120° between faces and 109° 28′ between edges arise not just in the regular tetrahedron but in any arrangement of soap films—provided there is no trapped air or, if there is, the pressures on the two sides of each film are equal (hence canceling each other out).

The films in a foam are slightly curved but can be approximated by plane faces: with this approximation, the two stated angles will be observed in the interior of a foam, though not for films near the foam's external surfaces. This fact is the basis of a curious calculation, which leads to the strange numbers with which I began this column. By pretending that foam is made from many identical polyhedra whose faces are regular polygons with angles of 109° 28′ (which is impossible, but who cares?), we can estimate the average numbers of vertices, edges and faces in any foam.

Plateau's observation about the 120° angle was quickly established as a mathematical fact. The proof is often credited to the great geometer Jacob Steiner in 1837, but Steiner was beaten to the punch by Evangelista Torricelli and Francesco B. Cavalieri around 1640. All these mathematicians actually studied an analogous problem for triangles. Given a triangle and a point inside it, draw the three lines from that point to the triangle's vertices and add up their lengths. Which point makes this total distance smallest? Answer: the point that makes the three lines meet at angles of 120°. (Provided no angle of the triangle exceeds 120°, that is—otherwise the desired point is the corresponding vertex.) The problem for soap films can be reduced to that for triangles by intersecting the films with a suitable plane.

In 1976 Frederick J. Almgren, Jr., then at Princeton University and Jean E. Taylor, then at the Massachusetts Institute of Technology, proved Plateau's second rule about 109° 28′ angles. They started by considering any vertex where six faces meet along four common edges. First, they showed that the slight curvature that occurs in most soap films can be ignored, so that the films can be taken as planar. They then considered the system of circular arcs formed by these planes when they intersect a small sphere centered on that vertex. Because the soap films are minimal surfaces, these arcs are "minimal curves": their total length is as small as possible. By the spherical analogue of the Torricelli-Cavalieri theorem, these arcs must always meet in threes at angles of 120°.

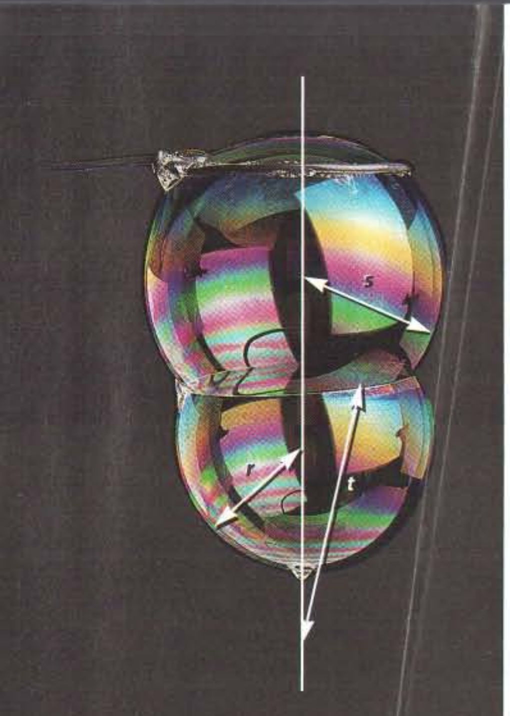
Almgren and Taylor proved that exactly 10 distinct configurations of arcs [*see illustration on this page*] can satisfy this criterion. For each case, they asked whether the total area of the films inside the sphere could be made smaller by deforming the surfaces slightly, perhaps introducing new bits of film. Any such cases could be discarded, because they could not correspond to a true minimal surface. Exactly three cases survived this treatment, the first three shown in the illustration above. The corresponding arrangements of film are a single film, three meeting along an edge at 120°, or six meeting at 109° 28′—just as Plateau observed.



PLATEAU'S RULE for the angle between four bubble edges was proved by considering the possible ways in which six faces meet. The vertices are enclosed in a sphere, on which the faces meet at angles of 120 degrees. As shown, only 10 shapes meet this criterion; of these, only the first three are physically plausible, because they correspond to minimal areas.

The detailed techniques required for the proof went beyond geometry into analysis—calculus and its more esoteric descendants. Almgren and Taylor used abstract concepts known as measures to contemplate bubble shapes far more complex than smooth surfaces.

The 120° rule leads to a beautiful property of two coalescing bubbles. It has long been assumed on empirical grounds that when two bubbles stick together, they form three spherical surfaces, arranged as in the illustration on the opposite page. This is the Double Bubble Conjecture. If it is true, the radii of the spherical surfaces must satisfy a simple relationship. Let the radii of the two bubbles be r and s and let the ra-



RADII of two coalescing bubbles (r and s) and their common surface (t) obey a simple relationship.

dius of the surface along which they meet be t. Then the relationship is

$$1/_r = 1/_s + 1/_t$$

This fact is proved in Cyril Isenberg's delightful book *The Science of Soap Films and Soap Bubbles* (Dover, 1992), using no more than elementary geometry and the 120° property.

All that remains is to prove that the surfaces are parts of spheres, and it is this that Hass and Schlafly achieved in 1995—but only by making the additional assumption that the bubbles are of equal volume. Their proof required the assistance of a computer, which had to work out 200,260 integrals associated with competing possibilities—a task that took the machine a mere 20 minutes! For further details, see "The Double Bubble Conjecture," by Frank Morgan in *Focus* (Mathematical Association of America), Vol. 15, No. 6, pages 6–7; December 1995.

One curious fact that is known about the unequal volume case is that whatever the double-bubble minimal configuration is, it must be a surface of revolution. The problem thus reduces to one about a system of curves in the plane. Despite this simple feature, the answer remains as elusive as it was when near-blind Plateau dipped his first wire frame into a bowl of sudsy water. SA

SCIENTIFIC AMERICAN

CORRESPONDENCE

Reprints: $4.00 each (minimum order, 10 copies) prepaid. Articles published within 3 months of current issue available. Write Reprint Dept., Scientific American, 415 Madison Ave., New York, NY 10017-1111.

Back issues: $9.95 each ($12.95 outside U.S.) prepaid. Most numbers available. Credit card (Mastercard/Visa) orders accepted. To order, fax (212) 355-0408.

Index of articles since 1948 available in electronic format. Write SciDex®, Scientific American Selections, P.O. Box 11314, Des Moines, IA 50340-1314, or call (800) 777-0444. E-mail: info@sciam.com

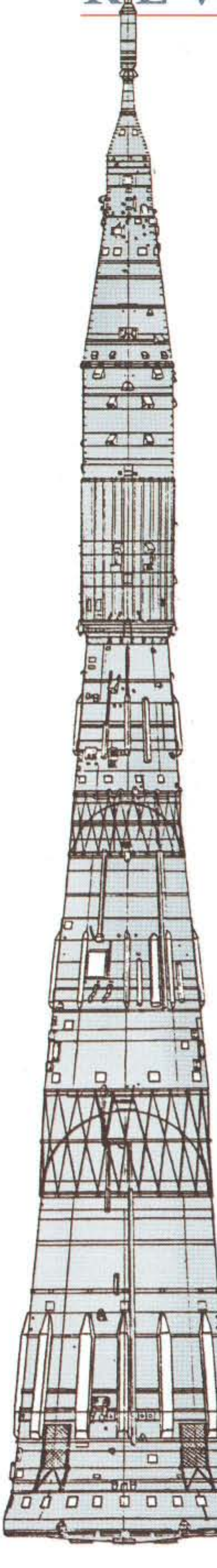
Editorial correspondence should be addressed to The Editors, Scientific American, 415 Madison Ave., New York, NY 10017-1111. Unsolicited manuscripts are submitted at the authors' risk and will not be returned unless accompanied by a stamped, self-addressed envelope. E-mail: editors@sciam.com

Advertising correspondence should be addressed to Advertising Manager, Scientific American, 415 Madison Ave., New York, NY 10017-1111, or fax (212) 754-1138. E-mail: advertising@sciam.com

Subscription correspondence should be addressed to Subscription Manager, Scientific American, P.O. Box 3187, Harlan, IA 51537. The date of the last issue of your subscription appears on each month's mailing label. For change of address, please notify us at least four weeks in advance. Please send your old address (mailing label, if possible) and your new address. We occasionally make subscribers' names available to reputable companies whose products and services we think will interest you. If you would like your name excluded from these mailings, please send your request with your mailing label to us at the Harlan, IA address. E-mail: customerservice@sciam.com

Visit our Web site at http://www.sciam.com/

REVIEWS AND COMMENTARIES



THE RACE INTO SPACE

Review by John M. Logsdon

Countdown: A History of Space Flight
BY T. A. HEPPENHEIMER
John Wiley & Sons, New York, 1997 ($30)

Korolev: How One Man Masterminded the Soviet Drive to Beat America to the Moon
BY JAMES HARFORD
John Wiley & Sons, New York, 1997 ($30)

In very different ways, these two books examine the space programs of the U.S. and the U.S.S.R. in the 1950s and 1960s and their close relationship to considerations of military security and national power. T. A. Heppenheimer is a professional writer on aeronautics and space topics; *Countdown* attempts in 350 pages to cover the full sweep of the development of 20th-century rocketry and space exploration. James Harford is an *amateur* in the classic sense: a gentleman scholar who, motivated by a longtime interest in the evolution of the Soviet space program, wrote his book after retiring from a career in aerospace work. *Korolev* probes the fascinating career of Sergei Pavlovich Korolev, until his death in January 1966 the anonymous "Chief Designer" of the Soviet missile and space efforts. By portraying how Korolev, through his resourcefulness and ingenuity, shaped the course of Soviet space development, Harford succeeds in letting "some light into the black hole of the Soviet social, political, and technological system in the pre-glasnost days."

Both books look back to an era when space achievements excited the public imagination and showcased a nation's technological and organizational competence. They demonstrate that the space race was real: accomplishments—even anticipated ones—by one country were a direct spur to a competitive response by the other. If there was ever any doubt that politics, pride and power, not a vision of an expansive future in space, provided the drive for the initial years of space activity, these books will lay that impression to rest. Space exploration, given its exorbitant costs, had to serve the highest interests of the state; no leader was ready to spend national wealth on journeying to the planets for the sake of human destiny.

DIRECT COMPETITORS: The U.S.S.R.'s N-1 (left) struggled to beat the U.S.'s Apollo rockets to the moon, but it failed in each of its four test launches.

CHARLES P. VICK

Current realities are remarkably different. The space race is over, and U.S.-Russian cooperation, not competition, is the centerpiece of today's primary large-scale endeavor—the International Space Station. Increasingly, space programs must demonstrate tangible benefits to receive scarce government support, and most growth over the next decade is likely to be the result of private-sector initiatives. Neither of these books has much to tell us about this new era in space, except in contrast to the situation four decades ago.

In *Countdown,* Heppenheimer assembles a lively account of the development of space activities in the U.S. and the Soviet Union, with only cursory attention to other countries. Given its scope, no single aspect of space development can be covered in much depth. The book includes vivid, if brief, descriptions of key personalities and events.

Although Heppenheimer draws on diverse materials, and the book has a useful bibliography, the author seldom acknowledges specific sources, and his footnoting can best be described as quirky. He is not totally accurate with respect to details such as dates and political nuances; *Countdown* should not be used as a single reference on space history, although most of the time, on most topics, it is quite dependable. There are few photographs, which is odd, given how much of the history of space has been visually recorded; the line drawings that substitute for photographs add little to the account.

Heppenheimer is skeptical of the reasons for putting humans in space, noting that "manned flight has become an enterprise unto itself, offering political value and the drama of symbolism, but little real utility." Without the story of human flight, however, he would not have had much of a book; only one of the 12 chapters covers robotic satellites and spacecraft. His analysis of the political and organizational underpinnings of the U.S. and Soviet space programs is largely derivative; this is not the source for insightful new interpretations of space policy and its relation to larger societal trends. *Countdown* is as good a one-volume overview of space as exists, but it is neither original nor definitive.

Korolev is the first in-depth biography in English of the man most responsible four decades ago for creating the rocket capability that allowed the Soviet Union to develop the first intercontinental ballistic missile and then to surprise the world by launching the first artificial Earth satellite. Korolev was then responsible, in October 1959, for the first mission to send back photographs of the

far side of the moon and, in April 1961, for launching the first human into space. In 1964, at the peak of his influence, he succeeded in convincing a skeptical Soviet leadership that the U.S.S.R. should enter the race to the moon. Then, in January 1966, he died during surgery, which revealed a cancer that would have given him only a few months to live in any event. Korolev's successors did not measure up to his capabilities, as the resounding failure of the Soviet lunar program testifies.

Harford has based his account of Korolev's life on extensive research in Russian-language documents and on interviews with almost all of Korolev's associates still alive. He writes in a clear, readable, almost casual style. Yet he is scrupulous in documenting his sources; his book will be of value for more formally trained scholars, although he is frank about its limitations—despite numerous attempts, he was unable to get access to the archives of the top levels of the Soviet government and Communist Party, and thus he cannot document from primary sources the debates over space policy that created the context within which Korolev worked.

Clearly fascinated by Korolev, Harford succeeds in sketching the many facets of the chief designer's complex character that allowed him, first, to maintain his dreams of spaceflight through a brief but harrowing experience in a Siberian gulag; then, by the end of World War II, to emerge as a leader in transferring German rocket engineers to the U.S.S.R.; and, finally, to convince Nikita Khrushchev that leadership in space was a key to projecting an international image of the Soviet Union as a success story based on communist ideology. Harford describes Korolev as "an engineer-manager of tremendous achievement and high ego" but also as someone who, in the words of one of Korolev's associates, "spread himself too thin and tried to keep everything under his control."

From Competition to Cooperation

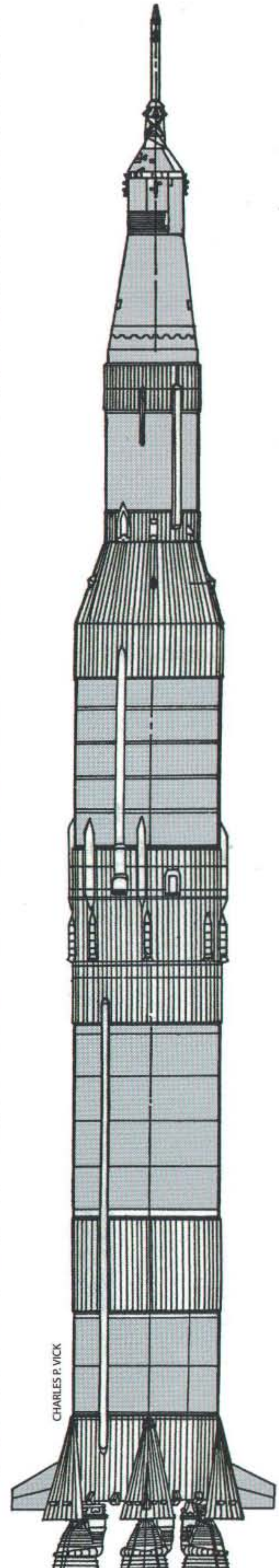
Of all the individuals central to the early years of the space race, Korolev may have been the most driven by the desire to be first in various space endeavors. In the U.S., President Dwight D. Eisenhower, despite advice to the contrary, refused to allow Wernher von Braun and his team to try to be the first to launch a satellite. Korolev, however, once his R-7 ICBM had been successfully tested in August 1957, convinced the Kremlin to accelerate the Soviet satellite effort with the explicit purpose of beating the U.S. into orbit. The first satellite, Sputnik 1, was a lightweight sphere built in one month solely for that objective. In contrast, Alan Shepard's initial flight in 1961 was delayed for six weeks while the von Braun team checked the rocket that would be his launch vehicle.

The subtitle of Harford's book—*How One Man Masterminded the Soviet Drive to Beat America to the Moon*—is somewhat misleading. If anything, the Soviet lunar program as designed by Korolev must be termed a failure. Harford comments, "As for whether the Russians would have beaten the Americans to the moon if Korolev had lived—the answer is a clear no. As with other heroes whose lives ended at the peak of their achievements, Korolev has been virtually canonized.... But as substantial as his achievements were, he was not omnipotent." Indeed, it is possible to judge from Harford's account that Korolev's career peaked in the early 1960s and that as the Soviet space program expanded, Korolev's influence waned. In addition to failing to obtain from the Soviet leadership the resources needed for the program, Korolev's personal rivalry with Valentin Glushko, the top designer of rocket engines in the Soviet Union, forced him to use 30 engines developed by another designer in the first stage of the N-1 lunar booster. (The U.S. Saturn V booster had five first-stage engines.) Controlling these engines so they worked in concert proved impossible, and the four test flights of the N-1 were all failures; the program was canceled in 1974.

As space activities enter their fifth decade, very different forces are at work from those at the start of the space age. Both books make clear the intimate link between the origins of the U.S. and Soviet space programs and the development of missiles to carry warheads on transoceanic trajectories. It is unlikely that a booster of sufficient power to carry out most early space missions would have been developed only for that purpose; in both countries, space vehicles were modified military rockets. Without the cold war, a space race would have been not only unlikely but perhaps impossible.

With the end of the cold war and the collapse of the Soviet Union, the rationale for U.S.-Soviet competition in space quickly evaporated. Leaders have recognized the benefits to both space programs—and indeed to the overall security and political relations between the two countries—of close cooperation in spaceflight. Given the problems of Russian society, only the country's human spaceflight program remains comparatively vigorous, and thus U.S.-Russian space cooperation has focused on flights of the space shuttle to space station *Mir* and on other aspects of collaboration on the International Space Station.

What if such cooperation, rather than vigorous competition, had been the norm years ago? This is not a totally speculative question. Although he is identified as the U.S. protagonist in the race to the moon, the historical record shows that President John F. Kennedy maintained throughout his



SATURN V carried Americans to the moon in 1969, decisively winning the race.

presidency great ambivalence regarding the wisdom of competing in space with the Soviet Union. From his inaugural address to just a week before he was assassinated, Kennedy sought ways of inducing the Soviet Union to cooperate in space as a means of symbolizing a changed, less contentious relationship. One recent book that is based on access to high-level Soviet government documents (*One Hell of a Gamble: Khrushchev, Castro and Kennedy, 1958–1964,* by Aleksandr Fursenko and Timothy Naftali, W. W. Norton, 1997) reveals that up to four days before he announced the Apollo program in May 1961, Kennedy was trying to place large-scale space cooperation on the agenda for his summit meeting in Vienna with Khrushchev two weeks later. The history of the world's space programs over the past 35 years would certainly have been different if Kennedy had been successful in gaining Khrushchev's agreement to such cooperation. At least a collaborative effort is happening now.

Sergei Korolev never met Wernher von Braun, but according to Harford's book, Korolev often compared himself with that Prussian aristocrat turned U.S. icon. One can only wonder what might have resulted if the two had worked together to advance their countries' joint space efforts.

JOHN M. LOGSDON is director of the Space Policy Institute at George Washington University's Elliott School of International Affairs.

PRESERVING THE WORD

Review by Paul Wallich

Into the Future: On the Preservation of Knowledge in the Electronic Age
A FILM BY TERRY SANDERS
NARRATED BY ROBERT MACNEIL
American Film Foundation, 1997
Airing January 13 on PBS

Print on paper is a little like democracy: the worst possible system except for all the others. Books are fragile, they are bulky, they are not easy to search through. They are certainly not suited to computerization, what with the extraneous niceties of typefaces, page layout and strictly linear organization. Yet printed volumes have endured half a millennium as readable as the day they came off the press, whereas digital data a mere 30 years old may have vanished past hope of retrieval.

Into the Future is itself an object lesson in how fast digital information becomes obsolete. One of the pioneering interactive-media companies whose workers and products appear on screen ceased operations shortly after being filmed. All the software whose images, over Robert MacNeil's narration, define "the Internet" is long since superseded.

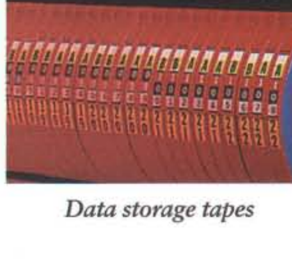
How fast do archivists have to run to stay in the same place? Just plain data must be recopied onto new media every 10 years to stay ahead of physical deterioration and the junking of machines that can read outdated formats. Given this galloping obsolescence, it seems ironic that the film's creators should have devoted a significant part of its time to the digitizing of paper archives, such as Spanish records of the conquest of the Americas. And yet they—and we—have no choice: the digital bug has infected us all, and interactive multimedia, with indexed and linked text, pictures and sound, have a convenience and impact that make conversion irresistible.

The growing popularity of the World Wide Web and its standard protocols offers some hope that publishers and archivists can format both old and new data in ways that will remain understandable for decades rather than months. But the Web brings its own complications. Nascent, undescribed genres of collected information live on the Web in forms that confound conventional notions of what a document is: if my Web page links to a dozen others scattered from Oslo to Perth, its content may be meaningless if those other authors change or delete their work. How should—or can—such an entity be archived without potentially archiving the entire Web?

Many Web pages are not even fixed documents in the most basic sense: software running on the Web server generates a string of HTML (hypertext markup language), complete with formatting, links and pictures "on the fly," in response to each incoming request. Two users who ask their Web browsers to open the same "document" (or URL, uniform resource locator) may see quite different things on their screens. Should an archivist be interested in saving one particular page from each URL, every single page that could ever be seen at that location, or the software and data used to generate all the pages?

As Michael Hawley of the Massachusetts Institute of Technology points out to the viewer in one sequence, the question is moot. The fastest connections on the Internet transmit a mere 45 million bits per second, and so even a single snapshot of the trillion or more bytes available on the Web would take weeks of computer and network time. Meanwhile new sites spring up every day, and some existing sites change their information from minute to minute.

In a sense, then, the Web has moved from a Newtonian to an Einsteinian paradigm: it makes no more sense to speak of the state of the Web "now" than it does to speak of synchronizing clocks located far apart. By the time information has gone from here to there, it is already out of date.

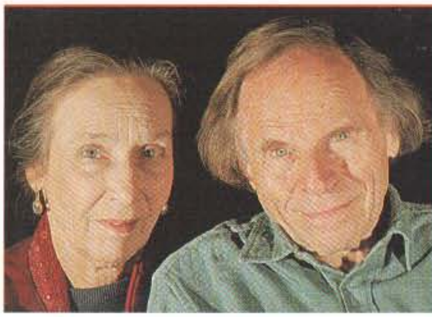


ROB JOHNS Liaison International

Data storage tapes

It may seem strange that a medium intended for the widest possible distribution of knowledge should demonstrate the impossibility of acquiring complete information. Then again, it is the nature of most of the interesting parts of the world that no map, no picture, can yield complete information about them. Only toy systems can be captured in their entirety. Where the Web was once a map for finding useful information in the "real world," it is now a territory where that information, ever changing, resides.

PAUL WALLICH is a contributing editor for SCIENTIFIC AMERICAN.



COMMENTARY

WONDERS

by Philip and Phylis Morrison

Wildfire

As fire is no part of the mineral kingdom, we find it surprisingly apt to discuss it as though it were one among the kingdoms of living things. Copious fire arose only after life crossed the margins of its watery world and came to thrive on dry land, under air of near-modern oxygen content, a state reached after 90 percent of earth history had passed.

We can divide fire, like the grasses, into wild and domesticated forms, both of them very widespread. Wildfire is not always truly wild. Like the cereal grasses, it may have been molded by human intervention and yet may still bloom under the open sky. Fully domesticated fire is different: its myriad species dwell confined within firebox, furnace or engine cylinder. Other forms that one might term fire—say, volcanoes and polar auroras—are less akin to life and remain outside the scope of this piece.

Fire feeds, just as animals do, on its two necessities: organics and the oxygen of ubiquitous air. Green plants synthesize themselves anew from the sun's brilliance. It is solar photons that power the reweaving of two stable molecules—water and carbon dioxide—into less tightly bound molecules. The very cell walls of most plants and the woody tissues, too, are largely fibrous bundles of cellulose, a defined polymer of glucose, the simplest of sugars, linked by the 100,000 into rings and chains of the atoms H, C and O.

Plant-stored energy is the chief metabolic support of the life of fire, as it is of our own lives. But we do not see fire grow regularly from the fields as we see green blades grow. Some special act of ignition, a tiny spark struck from a rock or a bolt of lightning, always precedes. Partly this is a limitation of our own perception: butter left exposed grows rancid; bright iron rusts. The fresh, greenish marble of the newly restored Parthenon was quarried from the same layers whose rock had given the old temple its rosy glow. The difference was those centuries in open air. All these changes come from slow oxidation by oxygen molecules, so slow they do not catch our eye as does sudden, impetuous fire.

Ignition is a huge acceleration of the rate at which molecular collisions recruit new partners to form more stable bonds by oxidation. The higher temperature thus achieved speeds up every molecular motion. New atomic partners arrive more often and are teased more readily out of the vibrating, rustling pile of atoms. On many scales, fire—even a minute flash—can ignite new fire, as long as the continued rate of energy release outmatches locally the unavoidable dilution as the energy spreads out. A trigger or a switch is not a good model for ignition, for triggers initiate changes very different in kind from their own actions. Fire itself ignites fire, to propagate where and when it can, like all of life.

The chemistry of real-world fire is not simple. The molecular end state is simple enough but reached only by a long ladder of branching chains. Every intermediate molecular group can collide again and again. Many paths are opened and left incomplete. In a real wood fire, as many as 100 significant molecular types may be transiently or permanently present during combustion. Incompleteness shows on the visible scale, too, as charred stems and twigs, as particles of impure carbon that comprise soot and smoke, and as acrid molecular side products. We note the energy release in flame itself, glowing gases in active reaction, and in pungent, transient crimson embers.

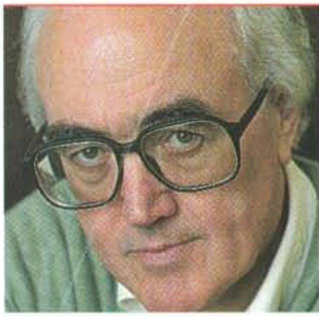
We owe all our human arts to the fire bringer.

The ignition of wildfire is still a shared responsibility. Human action is one major source, but an ancient rival is lightning, that electrostatic product made of water, ice and turbulent winds. Like humans, lightning prefers land to sea. On a single bad fire day in the western forests of the U.S., 100 new fires are set by lightning, quite independent of human presence.

We see many relics from the deeper past of fire, especially across the wide African savanna. Often woodlands lie on flats that fringe forested mountain slopes. Those retain forest only where they are sheltered from fire-bearing

Continued on page 91

DUSAN PETRICIC



CONNECTIONS

by James Burke

Anybody Out There?

DUSAN PETRICIC

We were having a bit of harmless fun the other evening after dinner, doing a little table rapping and glass moving, and somebody suggested we have a go at seeing if Charles Darwin was around. We did. He wasn't. Point being, somebody in our séance parlor party had been reading about the great unsolved mystery over who came up first with the idea of evolution.

Was it Darwin or Alfred Russel Wallace, the self-taught surveyor and insect freak? (In eight years in the Malay Archipelago, Wallace collected 125,660 *species* of creepy-crawly!) In 1858, while in Borneo, Wallace sent Darwin some thoughts on the origin of species and quicker than you could say, "I thought of it first," Darwin had published the Great Book. There are those who have suggested you know what. Perhaps we should have tried contacting Wallace himself. After all, he was a leading light in the spiritualist movement and proclaimed he'd never seen a medium who was a fraud.

This view was shared by a few other eminent scientists at the time, including hotshot physics professor Oliver Lodge. Like Wallace, Lodge was particularly interested in thought transference. He's best known perhaps for his work on another, equally hard-to-detect form of message transmission: electromagnetic waves. To deal with which, he came up with the idea of a small tube of iron filings that would cohere when a tiny radio signal passed through them and thus act as a detector. Lodge's gizmo paved the way for a Canadian, Reginald Aubrey Fessenden, who in 1906 succeeded in sending out continuous radio waves (as opposed to the intermittent signals Marconi in Italy and others elsewhere were using) that were capable of carrying voice messages.

At the news of this broadcast, the United Fruit Company promptly went bananas. Here was the perfect way for mass fruiterers to arrange it so that their ships and trains got to the same place at the same time. These niceties matter in the banana trade because bananas grow so fast you can have several harvests a year. Fast growing means fast ripening, so getting the fruit to the consumer ASAP is advisable. I know all this because I've read a terminally boring tome by Alphonse Candolle, top banana in bananas back in the 19th century (okay, no more fruit jokes), who ran the Geneva Botanical Gardens after he took it over from his father.

Candolle *père* was pals with another Geneva boffin, name of Horace Bénédict de Saussure. This guy became a world-class biggie in geologic processes when his publications fostered the realization that the planet had been around for a little longer than the up-to-then official 5,000-odd years. This in turn helped lay the groundwork for the aforementioned Darwin. (Because de Saussure was now so famous, and because he was also nuts about Mont Blanc, the Swiss considered changing the mountain's name in his honor. But "Mont de Saussure" didn't have quite the same ring.)

The United Fruit Company promptly went bananas.

Anyway, de Saussure had a favorite pupil, François Argand, whom he introduced to the Paris science crowd, and by the autumn of 1783 Argand was busy helping the Montgolfiers launch their demo balloon flight for the National Academy of Sciences. A few weeks later the two brothers substituted humans for ducks and chickens, and the first manned balloon ascent took place. To the excited amazement of Benjamin Franklin, who promptly went back to the States and made a fuss along the lines of "If the French have balloons, so should America." As a result, nothing of note happened. Indeed, in France, Napoleon railed against the whole idea of this particular use of French hot air, and so the nascent French Balloon Corps was disbanded. Bad news for one Nicholas Conte, its instigator, who went off and invented a new pencil lead. But that's another column.

Meanwhile back in the U.S. came the Civil War and with it a resurgence of interest in things aeronautic, in the person of Professor (for some odd reason American balloonists were given this academic title) Thaddeus Lowe. His checkered flying career reached its height (and so did he) on June 2, 1862, when he hovered 2,000 feet above the battle of Chicahominy in his balloon *Enterprise*. The *Times* of London reported that Lowe was able to detail every movement of the Confederate armies below, to his Union boss (also below). This was achieved by means of a telegraph wire running down the anchoring rope to the ground.

The man who put Lowe up to this trick was George B. McClellan, general of the army of the Potomac and a whiz kid, who saw the intelligence potential of what Lowe and his vehicle could do. The other intelligent thing McClellan did was to set up a Secret Service department for the army, with the aid of an ex-barrel maker turned private detective whom he had employed before the war to keep an eye on the property of the Illinois Central Railroad, of which McClellan was vice president at

the time. If I also tell you that the railroad's lawyer was Abraham Lincoln, you'll guess who this gumshoe was. Thanks to these friends in high places, Allan Pinkerton would go on to set up the country's most famous detective agency. It was Pinkerton who first recognized that crooks had a modus operandi. He was also a master of disguises. And his casebook read like a *Who's Who* of the underworld, including Jesse James, Butch Cassidy and the Sundance Kid.

But Pinkerton's most notorious effort involved a bunch of Irish terrorists (or anarchists or radicals or whatever) called the Molly Maguires, who were operating in the Pennsylvania coalfields. These operations involved arson, general mayhem and murder. Pinkerton decided to infiltrate the gang and in 1873 sent in James McParlan, who had the right qualifications for the job: he was Irish, Catholic and tough. In no time at all, McParlan was doing too well. That is to say, the Mollies liked him so much he was soon being invited to join their assassination squad. Desperate to avoid this, McParlan persuaded the Mollies that he was a drunk by taking to drink. Too effectively, because he became a hopeless alcoholic and would eventually die of the effects, in obscurity, in Denver. But not before his two years of weekly secret reports to Pinkerton had fingered the Mollies and led to their capture and several executions.

McParlan's work was not, however, to go totally unrecognized. In 1914 he became the internationally acclaimed hero of a novel entitled *Valley of Fear.* Well, he *would* have been such but for the fact that the author ended up naming the book's detective protagonist something else. McParlan's heroics were fictionally appropriated by (the already internationally famous) Sherlock Holmes. Given McParlan's fate, it's ironic that *Valley of Fear* was to be Sherlock's last case, too.

After which his creator, Sir Arthur Conan Doyle, turned to expressing himself through a different medium. The kind that sat around tables and got up to what I was playing at the other night. Because in 1914 Doyle stopped writing and took over where Wallace and Lodge had left off: he became a leading light in the Society for Psychic Research.

Hope you found this column positively entrancing. SA

Wonders, continued from page 89
strong winds. Locations more exposed to wildfire soon surrender trees to grass. Fire favors short-lived grasses; its long absence brings older, woodier bush, even trees. The grazing herds depend on plentiful grass; when choking bushes fill in grassy plains, they drive away the wondrous hoofed menagerie. One big bird, the bald ibis, is found only where lightning often sets fire, and it disappears where fire is suppressed. That bird feeds well on fire's leavings, perhaps some half-cooked turtle too slow to flee.

What of our human relation to fire? Fire making has been practiced by only one or two species. First used by our forebears *Homo erectus* and now by ourselves, fire is a tool as sovereign as language. A splendid book, *World Fire,* by Stephen Pyne of Arizona State University—the impetus for this column—offers a clear test of fire's importance to culture: remove fire and see what remains. He concludes, in agreement with the Greek myth, that we owe all our human arts to the fire bringer: "What would remain is a large talking chimpanzee, one reduced to following the spoor of nature's fires, a forager stirring the ashes of an Other's abandoned camps."

Holding fire as we have for a million years, we do much more. When our ancestors foraged, they cooked to gain new sources of food, lighted the evening darkness against big cats, set wide plains afire in season to lure the herds to new grass and opened easy paths through dense underbrush. Wildfire is a powerful, capricious friend to wandering bands, but it appears as a lifelong enemy to those who demarcate fields, pastures and woods and hold deeds into perpetuity.

When humans settled to tend crops, fire was the oldest ally and first surrogate for the heavy work of ax, hoe and plow. Now that our numbers are in the billions, fire still channels the mainstream of industry. Every year worldwide the satellites show a few gigatons of biomass carbon blazing in rural fires, part of the annual cycles of cultivators and pastoral people. The yearly mass of carbon that burns in confinement—almost all our coal, oil and gas—is not yet twice that much. The torch is busy, but so are the engineers, and the stakes rise higher each decade. We await fire's future as our own. SA

WORKING KNOWLEDGE

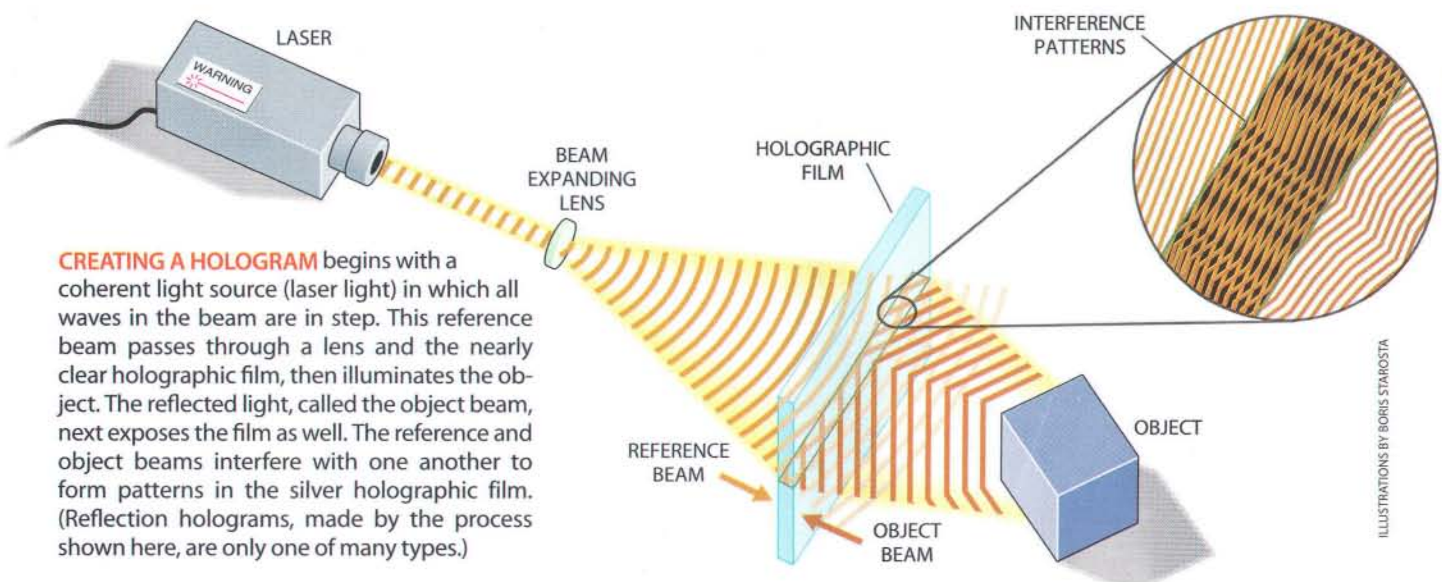
HOLOGRAMS

by Stephen A. Benton
Head, Spatial Imaging Group
Media Laboratory
Massachusetts Institute of Technology

A hologram is a recording of a three-dimensional optical image made on very fine grained film using beams of laser light. Unlike photography, which records only the intensity of each light wave reflecting off an object (producing light and dark areas on a film), holography registers both the intensity and the direction, or phase, of the light. Information about intensity and direction is encoded by the degree to which the crests and troughs of the reflected waves are in step with those of a reference wave. In-phase waves produce bright interference patterns, whereas out-of-step waves produce dim patterns.

When white light shines on developed holographic film, the interference patterns act like tiny mirrors positioned at myriad angles. These mirrors bounce light off the surface of the hologram in exactly the same directions at which it originally reflected from the imaged object. Each eye sees a different view because the intensity of the reflected waves varies with their direction, so the observer can perceive depth.

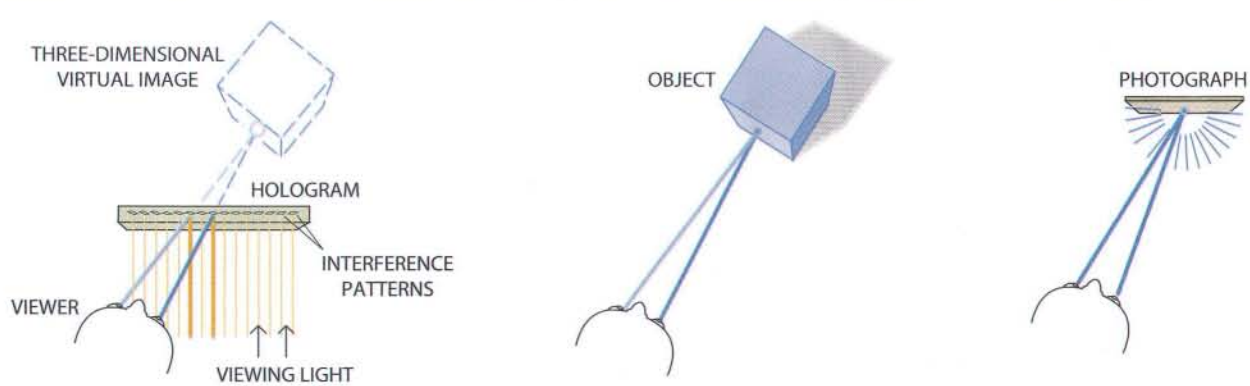
A single hologram is thus equivalent to many conventional photographs, each taken from a different perspective and focused at a different depth. In fact, it is fair to say that a hologram is worth a thousand pictures.



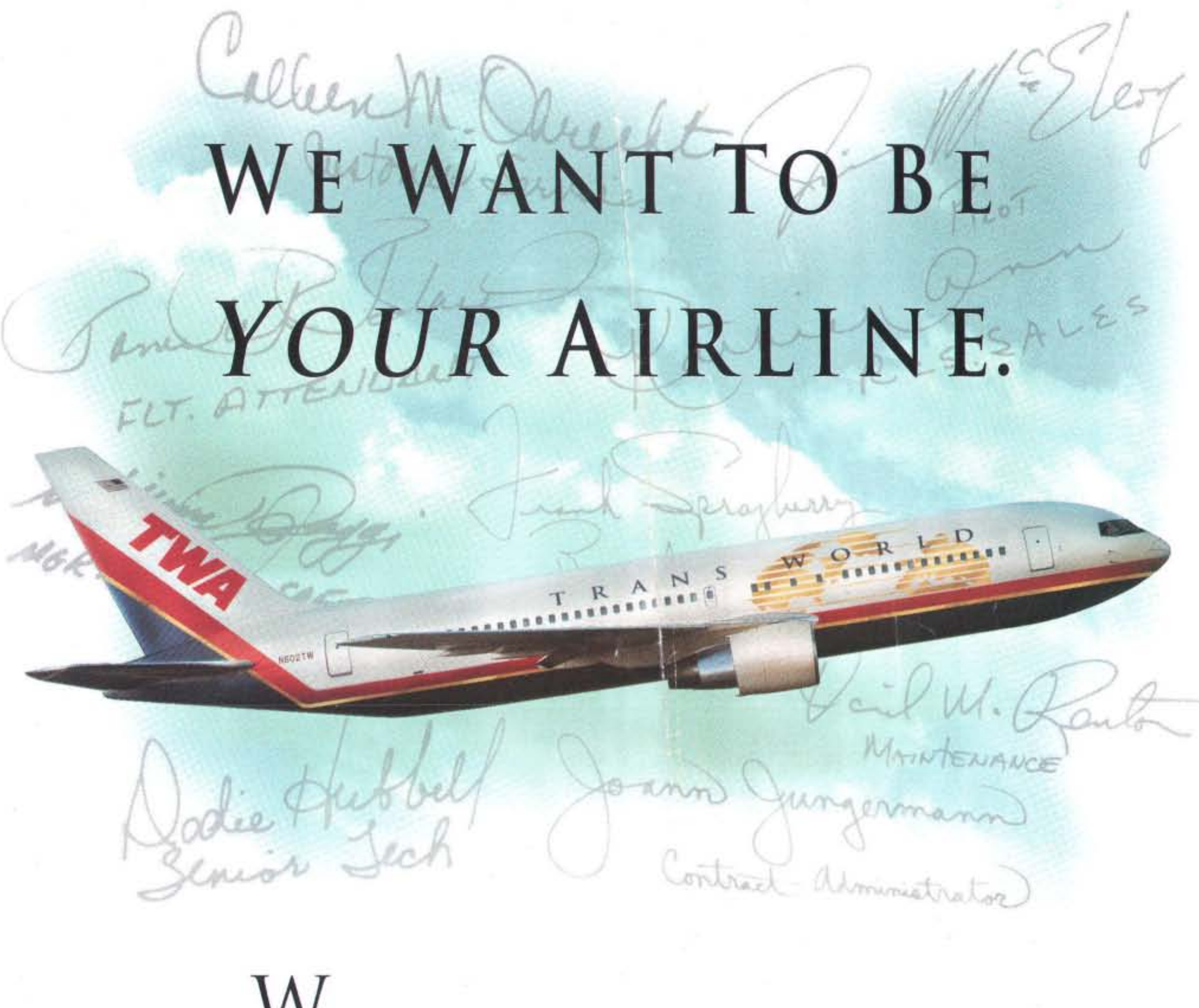
CREATING A HOLOGRAM begins with a coherent light source (laser light) in which all waves in the beam are in step. This reference beam passes through a lens and the nearly clear holographic film, then illuminates the object. The reflected light, called the object beam, next exposes the film as well. The reference and object beams interfere with one another to form patterns in the silver holographic film. (Reflection holograms, made by the process shown here, are only one of many types.)

ILLUSTRATIONS BY BORIS STAROSTA

VIEWING A HOLOGRAM involves training light on the film from the same angle as the original reference beam. The interference patterns in the silver film diffract and reflect the light so as to re-create the orientation and intensity of the waves in the original object beam. Each eye focuses light from a separate interference pattern for a given point (*left*). By doing this for each point in the image, the observer sees a three-dimensional virtual picture floating behind the hologram. By varying the intensity of light with the angle at which it is viewed, the hologram replicates the way an observer sees an object in the real world. The comparison is shown by the differing shadings for both the left and right rays in the three-dimensional image (*left*) and the real-world object (*center*). A two-dimensional photograph, though, reflects the same intensity of light in all directions (*right*).



WE WANT TO BE *YOUR* AIRLINE.



We know it's a big request. But we wouldn't be asking for your business if we weren't ready to earn it. In fact, we're already working to make Trans World Airlines your airline of choice. The airline you deserve.

You'll see it in the bold colors of the 30 new planes we're adding to our fleet. More importantly, you can see it in every TWA® employee owner. Because we're making a statement too. About on-time performance. Reliability. The things you want from an airline. The things each of us is dedicated to delivering.

We're already making a difference. And we're just getting started. Every day, with every flight, we're making TWA a better airline. The kind of airline we're proud to own. The kind of airline you'd be proud to call your own.

TWA®

Call your travel professional or TWA at 1-800-221-2000. Visit us online at www.twa.com